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"SHOCK PROPAGATION AND SUPERSONIC DRAG IN LOW TEMPERATURE PLASMAS" Support for AFOSR-SPONSORED WORKSHOP: "Understanding and Control of Ionized High-Speed Flows." Held at Princeton University, Princeton, NJ, Feb. 26-27, 1998

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P00002

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION
REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

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13. ABSTRACT (Maximum 200 Words)

This grant supported an Air Force-sponsored workshop, "Understanding and Control of Ionized High-Speed Flows," which was conducted at Princeton University, February 26-27, 1998. In recent years, there has been a great deal of interest in the formation mechanisms and properties of air plasmas. This interest is, in part, motivated by experiments conducted in Russia and in the United States which indicate shock propagation in weakly ionized air plasmas is at a higher velocity than would be predicted by presently understood models. If this is, indeed, the case, such plasmas could be used for supersonic/hypersonic drag reduction. In addition, atmospheric plasmas could influence flow control devices, electromagnetic attenuation, and hypersonic propulsion systems. As a consequence, the formation of such plasmas in atmospheric pressure environments, and the study of the properties of these plasmas, are of significant national interest.

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FINAL TECHNICAL REPORT (Dated 8/28/01)

AFOSR GRANT #F4920-97-1-0497, P00002
(150-6756)

**“SHOCK PROPAGATION AND SUPERSONIC DRAG IN
LOW TEMPERATURE PLASMAS”**

SUPPORT FOR:

AFOSR-SPONSORED WORKSHOP ENTITLED:
“Understanding and Control of Ionized High-Speed Flows”
Princeton University
Princeton, NJ 08544
February 26-27, 1998

ABSTRACT

This grant supported the costs of an Air Force-sponsored workshop, “Understanding and Control of Ionized High-Speed Flows,” which was conducted at Princeton University, February 26-27, 1998. In recent years, there has been a great deal of interest in the formation mechanisms and properties of air plasmas. This interest is, in part, motivated by experiments conducted in Russia and in the United States which indicate shock propagation in weakly ionized air plasmas is at a higher velocity than would be predicted by presently understood models. If this is, indeed, the case, such plasmas could be used for supersonic/hypersonic drag reduction. In addition, atmospheric plasmas could influence flow control devices, electromagnetic attenuation, and hypersonic propulsion systems. As a consequence, the formation of such plasmas in atmospheric pressure environments, and the study of the properties of these plasmas, are of significant national interest.

DISCUSSION

The purpose of the workshop was to highlight the basic science issues involved with controlling high-speed flows using weakly-ionized plasmas. The specific objectives of the two-day meeting were to review recent experimental/theoretical research in this area, and to exchange ideas/understanding on the basic flow physics of the problem, and to discuss future research directions. Princeton University was a natural location for this workshop since work is underway here to examine both drag characteristics and electron discharge physics associated with weakly ionized plasmas.

Sixty individuals, each of whom is considered a leading authority on this issue, attended the two-day workshop (a full listing of the participants is located in Appendix A). The first day of the workshop consisted of four sessions on an agenda of twelve speakers and covered the following topics:

Session I: "Introduction to the Problem" (presentations by B. Ganguly of AFRL and A. Auslender of NASA LaRc).

Session II: "Aerodynamics of Ionized Flow" (presentations by R. Miles of Princeton University, J. Shang of AFRL, N. Malmuth and V. Soloviev of Rockwell Science, and V. Subramanian of The Ohio State University).

Session III: "Theory and Computation of Ionized Flows" (presentations by G. Karniadakis of Brown University, K. Powell of the University of Michigan, and S. Nazarenko of the University of Arizona).

Session IV: "Plasma Generation and Maintenance" (Presentations by S. Kuo of Polytechnic University, J. Kline of Research Support Instruments, and W. Rich of The Ohio State University).

The second day of the workshop, the participants were divided into four separate working groups for further discussion, followed by debriefings and laboratory tours at Princeton.

Appendix A is a complete record of the two-day workshop and includes the final agenda for the meeting, the complete list of participants and their contact information, as well as copies of each of the presentations for all of the four topic areas listed above.

Princeton University

School of Engineering and Applied Science
Department of Mechanical and Aerospace Engineering
P.O. Box CN5263
Princeton, New Jersey 08544-5263



Appendix A

FINAL AGENDA

AFOSR-SPONSORED WORKSHOP:

"UNDERSTANDING AND CONTROL OF IONIZED HIGH-SPEED FLOWS"

February 26-27, 1998

MEETING LOCATION: Convocation Room (C217) Engineering Quadrangle
Olden Street, Princeton, NJ 08544

THURSDAY, FEBRUARY 26, 1998:




7:30 AM	SIGN-IN/COFFEE	
8:00 AM	OPENING REMARKS:	G.L. Brown--Chairman, MAE Dept., Princeton R. Miles--Princeton S. Walker--AFOSR
8:30 AM	SESSION I:	<u>INTRODUCTION TO THE PROBLEM</u> B. Ganguly--AFRL, A. Auslender--NASA LaRC
9:30 AM	DISCUSSION	
10:00 AM	BREAK	
10:30 AM	SESSION II:	<u>AERODYNAMICS OF IONIZED FLOW</u> R. Miles--Princeton, J. Shang--AFRL, N. Malmuth/V. Soloviev--Rockwell Science V. Subramanian--OSU
11:30 AM	DISCUSSION	
12:00 PM	LUNCH	
1:30 PM	SESSION III:	<u>THEORY AND COMPUTATION OF IONIZED FLOWS</u> G. Karniadakis--Brown U., K. Powell--UM, S. Nazarenko--UA
2:30 PM	DISCUSSION	
3:00 PM	BREAK	
3:30 PM	SESSION IV:	<u>PLASMA GENERATION AND MAINTENANCE</u> S. Kuo--Polytechnic Univ., J. Kline--RSI, W. Rich--OSU
4:30 PM	DISCUSSION	
5:00 PM	FIRST DAY WRAP-UP	
6:00 PM	RECEPTION, Prospect House	

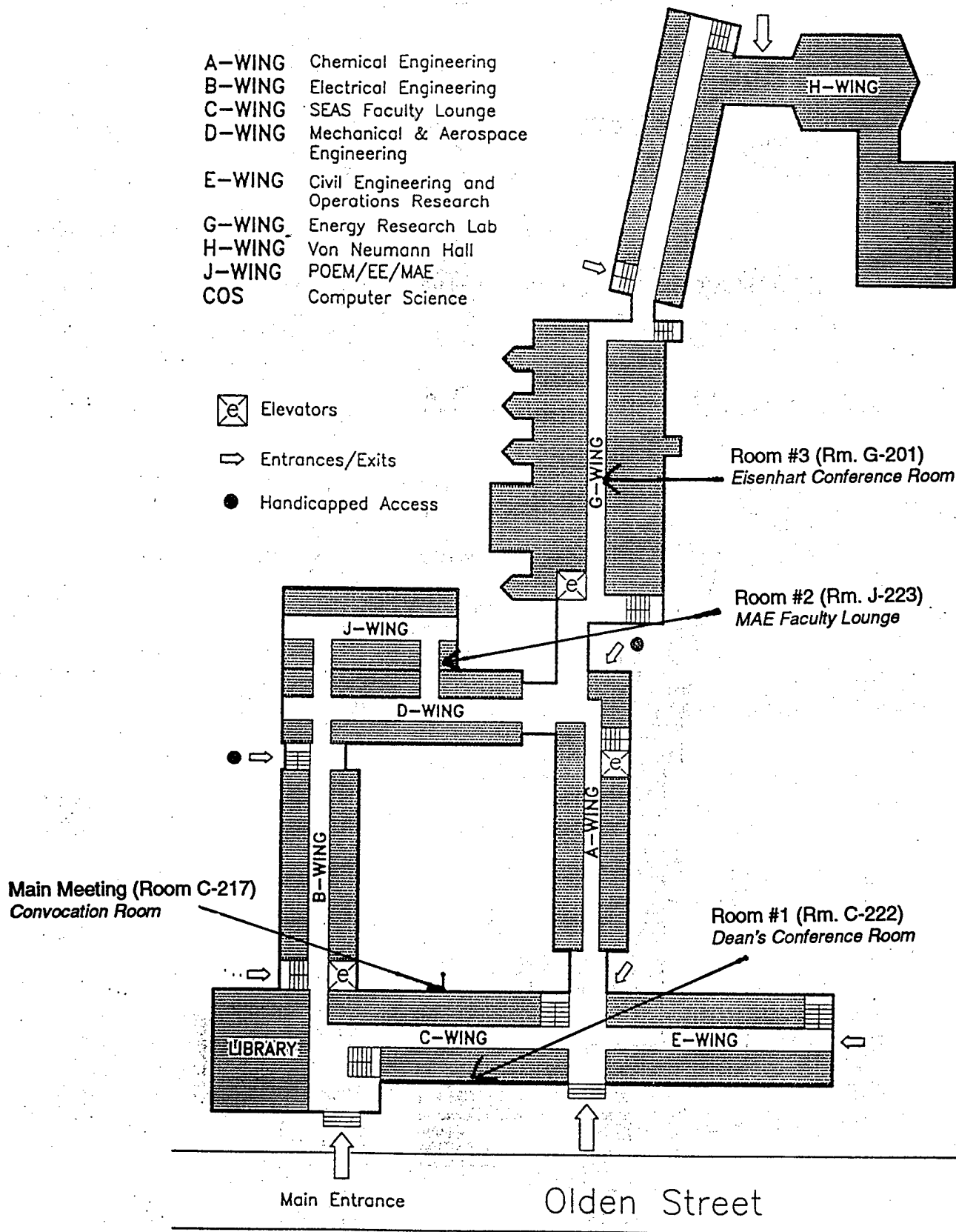
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ENGINEERING QUADRANGLE

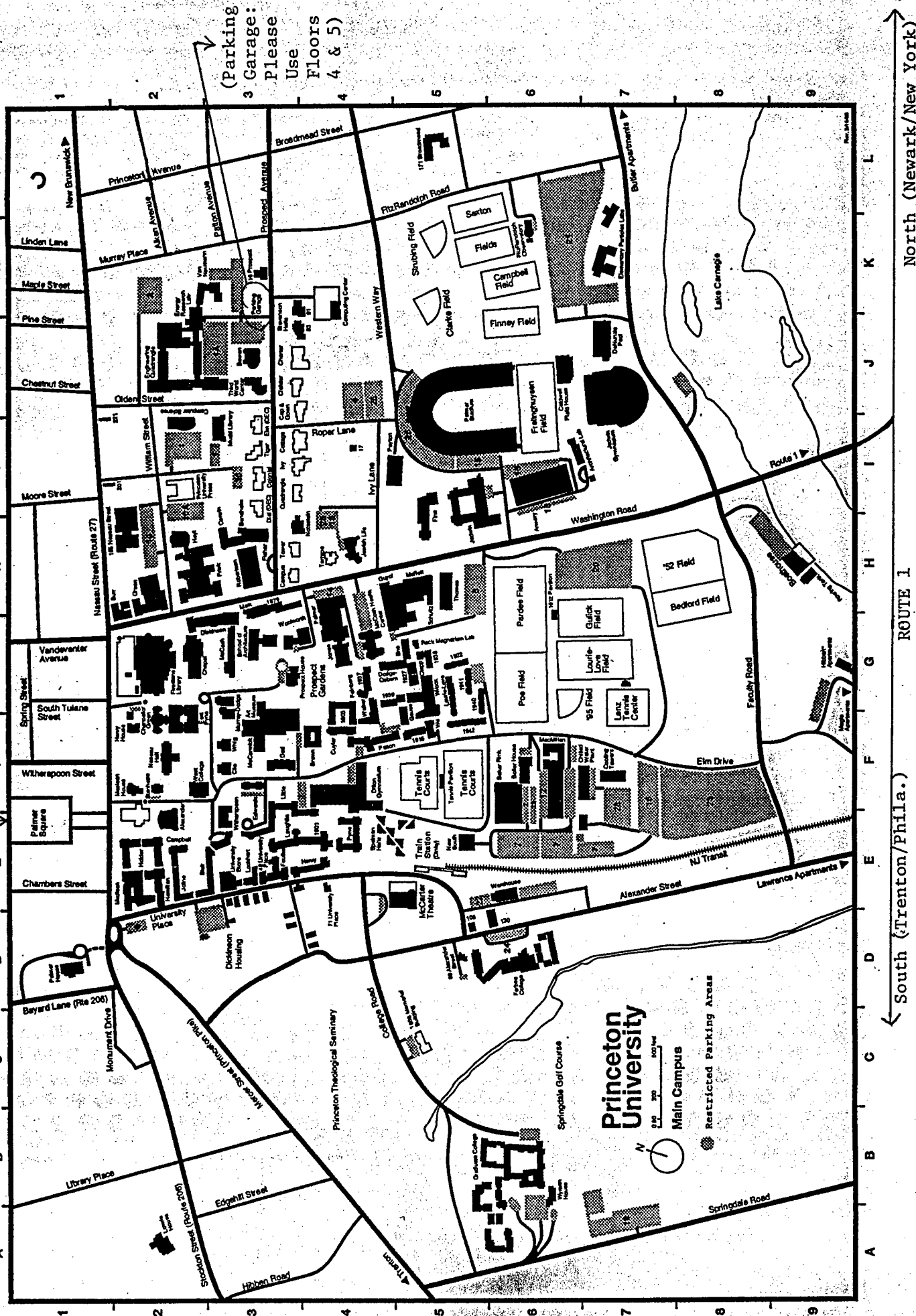
- A-WING Chemical Engineering
- B-WING Electrical Engineering
- C-WING SEAS Faculty Lounge
- D-WING Mechanical & Aerospace Engineering
- E-WING Civil Engineering and Operations Research
- G-WING Energy Research Lab
- H-WING Von Neumann Hall
- J-WING POEM/EE/MAE
- COS Computer Science

-  Elevators
-  Entrances/Exits
-  Handicapped Access



COMPUTER SCIENCE BUILDING

Restrooms are located in the corners of the building where 2 wings meet.



PARTICIPANT LIST

AFOSR-SPONSORED WORKSHOP: "UNDERSTANDING & CONTROL OF IONIZED HIGH-SPEED FLOWS"

PRINCETON UNIVERSITY
FEBRUARY 26-27, 1998

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Understanding and Control of Ionized High-Speed Flows

AFOSR-Sponsored Workshop

Princeton University

26-27 Feb 98

NEW WORLD VISTAS (NWW)

- **41 Technologies Identified By AFMC And The Air Force Scientific Advisory Board**
- **32 NWW Technologies To Receive Basic Research Support**
- **\$14.8M Budget For FY 1997**

HYPERSONICS

Objectives

- Investigate Advanced Propellants And Cooling Concepts To Enable Hydrocarbon-Fueled Mach 8+ Aeropropulsion And Combined Cycle Propulsion
- Examine Electromagnetic Manipulation Of Ionized Flowfields To Improve Hypersonic Vehicle Performance



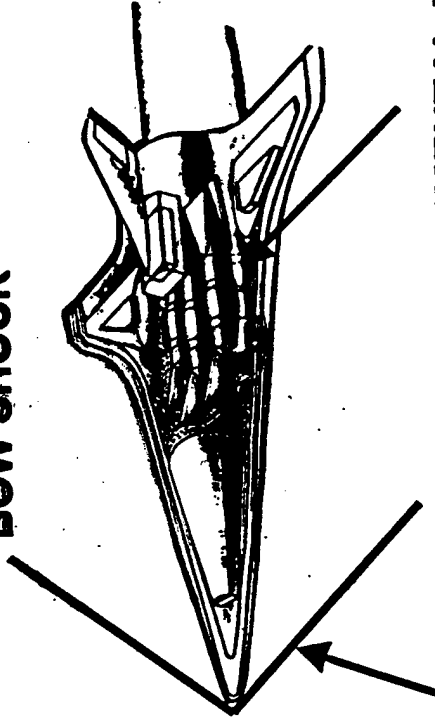
NEW WORLD VISTAS POWER PROJECTION AND MOBILITY

TOPIC 08 - HYPERSONICS

**RESEARCH ISSUE: IMPACT OF WEAKLY IONIZED FLOWS ON
VEHICLE/PROPULSION SYSTEM PERFORMANCE**

**RUSSIAN AYAKS FLIGHT
VEHICLE CONCEPT**

BOW SHOCK



**MEASUREMENTS INDICATE THAT
UNSTEADY ANALYSIS IS REQUIRED
TO DESCRIBE ENERGY TRANSFER
BETWEEN SHOCKS AND NONEQUILIBRIUM
MEDIA (GANGULY, AFRL/PR)**

**EXPERIMENTAL RESULTS SHOW THAT
REACTION WITH IONIZED AIR CAUSES
HYDROCARBON FUEL COMPONENTS
TO DECOMPOSE AND FORM REACTIVE
FREE RADICALS (MORRIS, AFRL/VS)**



Background



- Many experiments have shown large changes in shock strength, speed, and stand-off distance in weakly-ionized flows
- Complete analysis of proposed mechanisms for the observed shock dynamics is lacking
- US interest/research is increasing -
USAF June 97 workshop



Purpose of Workshop



- Highlight basic science issues involved with controlling high-speed flows using weakly-ionized plasma
 - Review recent basic research in the area
 - Technical exchange on flow physics
 - Discuss future directions

FINAL AGENDA

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12:00 PM	LUNCH/LABORATORY TOUR



Rules of Engagement



- Let's keep this science-oriented but relevant; we'll let someone else actually build AJAX
- Let's really attempt to better understand this stuff before we leave
- Let's critique the work, but not criticize the people
- Please don't say, "It's just a thermal effect"; prove it.
- Don't be afraid to ask questions; we have people from many diverse technical backgrounds here
- Government people never say stupid things (by default)
- Please treat the second day as your collective chance to shape the future AF basic research investment in this area
- Let's have fun - 2 days without email, voice mail, dept. chairs, supervisors, etc.

AFOSR

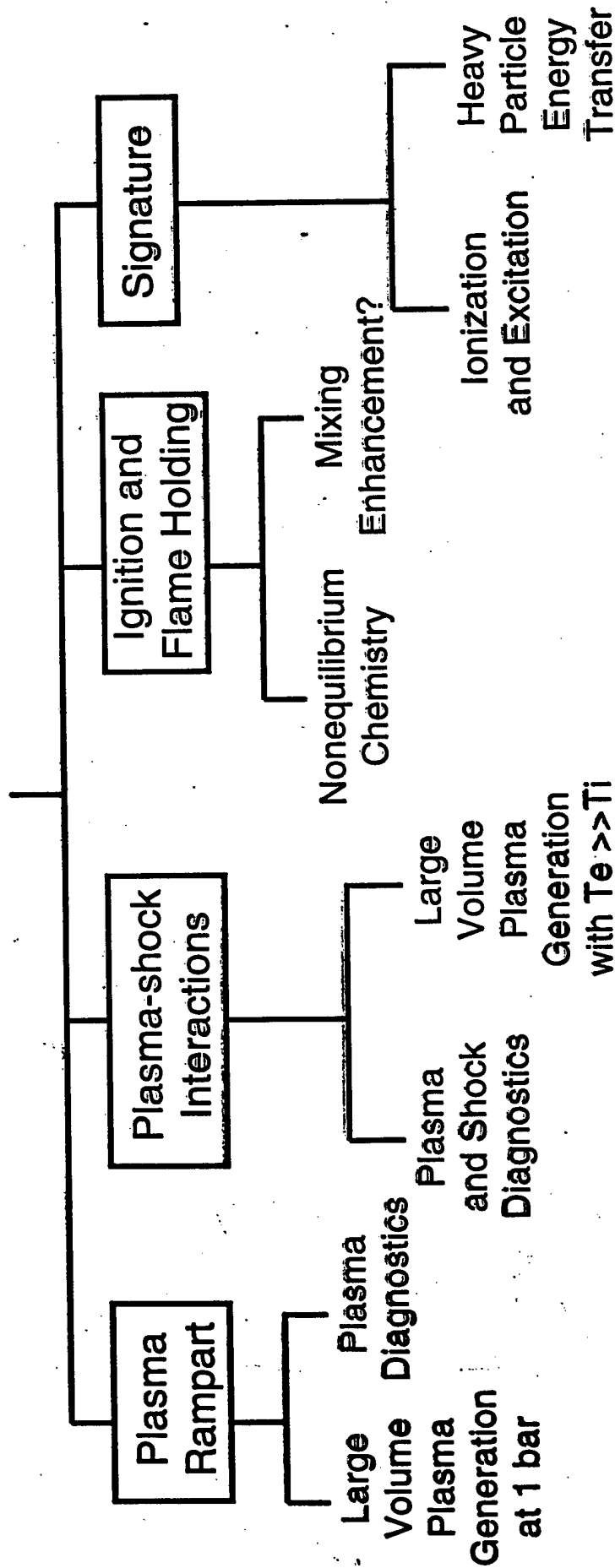
Workshop

Princeton Univ

Feb 26, 1998

Dr. Bish Ganguly

Nonequilibrium Air Plasma



POTENTIAL PAYOFFS OF NONEQUILIBRIUM PLASMAS TO HYPERSONICS

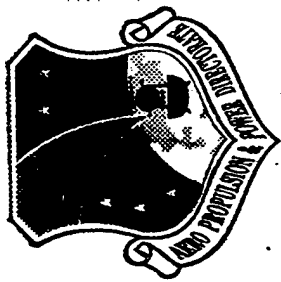
- Thermal problem minimized - shock wave dissipation by nonequilibrium plasmas
- Combustion efficiency improvement - mixing enhancement by plasma interactions
- Drag reductions through boundary layer control
- Improve ignition and flame holding for subsonic to hypersonic combustor by nonequilibrium plasma chemistry

EXPERIMENTAL OBSERVATIONS OF PLASMA-SHOCK INTERACTIONS

- Shock wave dispersion, damping and velocity increase (super thermal) are observed in glow discharges of both atomic and molecular gases
 - a. fractional ionization - 10^{-7} to 10^{-3}
 - b. gas temperature - 300 to 1400 K
- Similar features are not observed in thermal plasmas
- Weak magnetic field impacts sound velocity
- Sound velocity change depends on T_e
- UV illumination of the plasma is claimed to increase speed of sound in plasma

CURRENT STATUS OF THE RESEARCH RESULTS

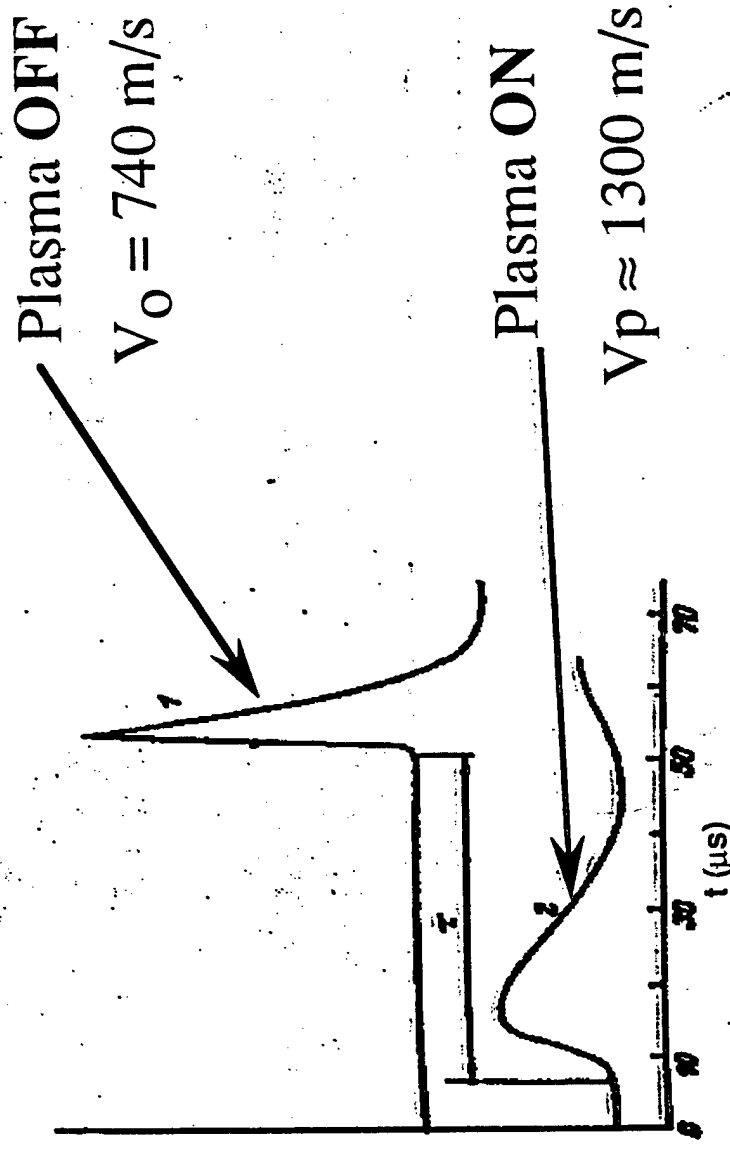
- SEVERAL GROUPS HAVE REPORTED INCREASED DISPERSION AND DAMPING OF SHOCK WAVES IN WEAKLY IONIZED PLASMAS, ALSO HIGHER SHOCK PROPAGATION VELOCITIES
- SOME OF THE RESEARCHERS ASCRIBED THE EFFECTS TO THE NONEQUILIBRIUM PLASMAS, OTHERS TO THE TEMPERATURE GRADIENT FORMED IN PLASMAS
- ACCURATE THEORETICAL MODEL EXISTS FOR SMALL AMPLITUDE AUDIO FREQUENCY ACOUSTIC WAVE PROPAGATION IN PLASMAS
- ACCURATE MODEL DOES NOT EXIST FOR SHOCK WAVE PROPAGATION IN NONEQUILIBRIUM PLASMAS



Shock Wave Propagation in a Weakly Ionized Low-pressure Discharge

Plasma Parameters

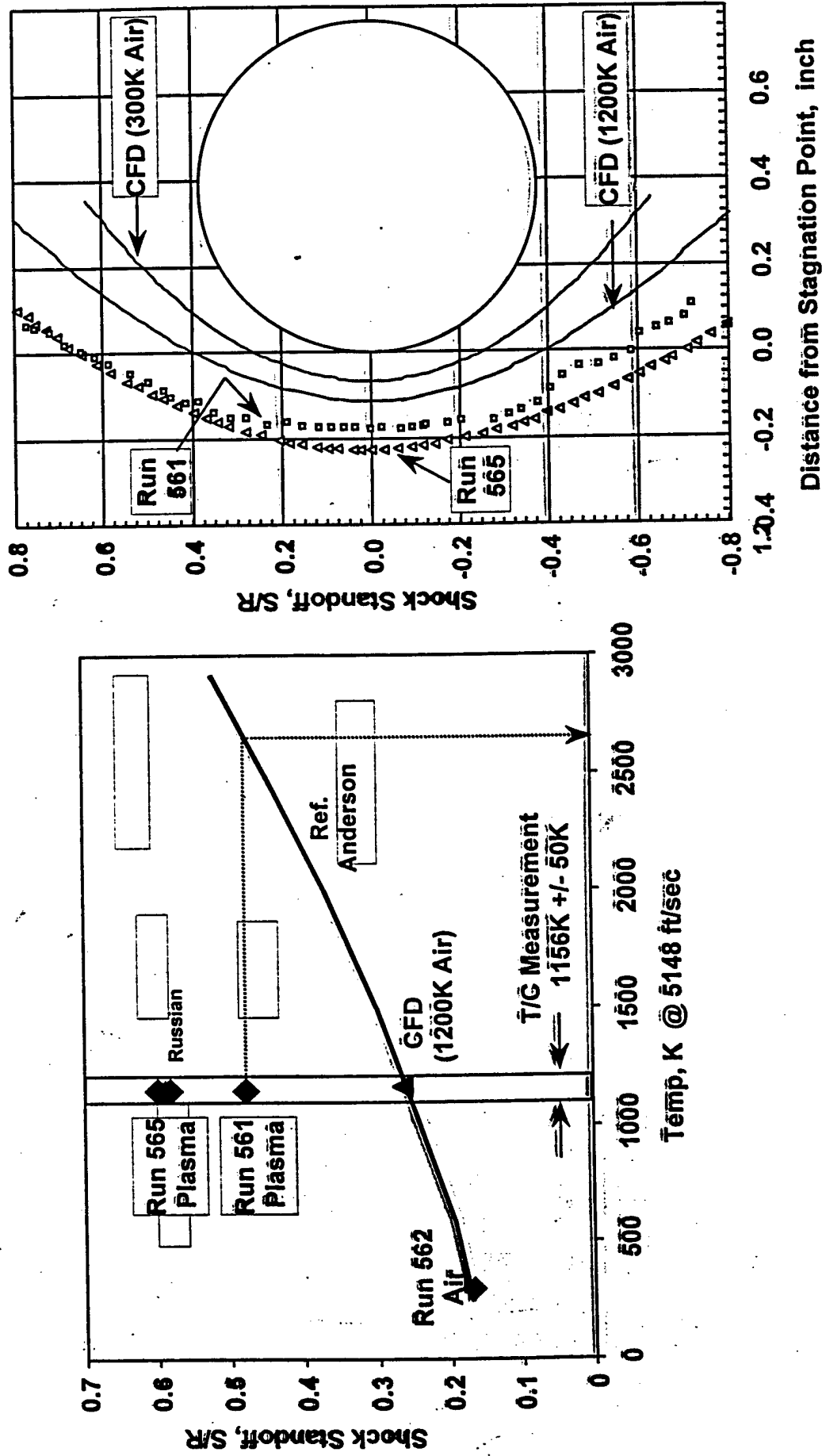
$p = 30 \text{ torr}$
 $J = 3 \text{ mA/cm}^2$
 $T_g = 800 \text{ K}$



A. I. Klimov et al., Sov. Tech. Phys. Lett. 8, 192 (1982)

Shock Standoff Comparison to Predictions

(0.75 in. diam, 30 torr)

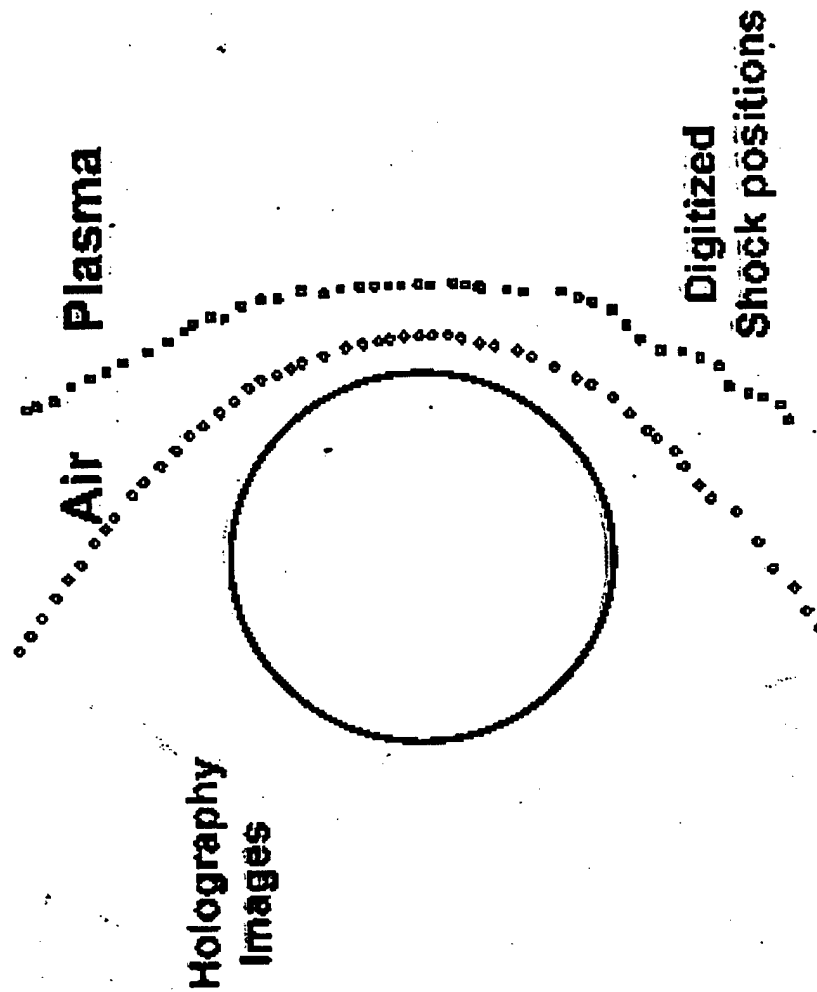
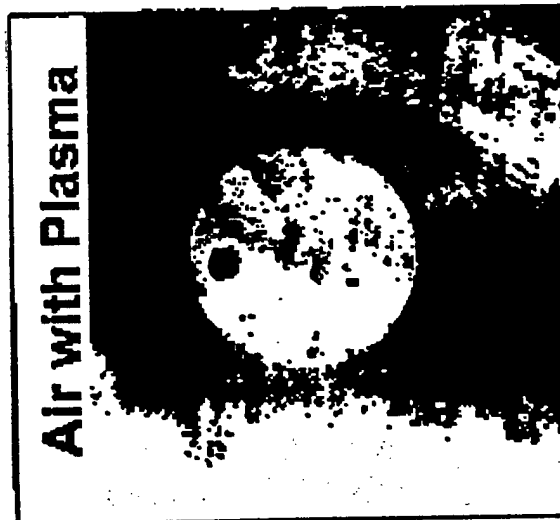
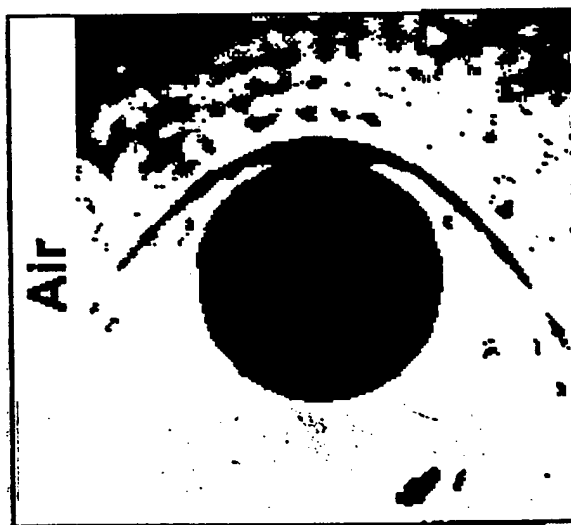


RESEARCH TOPICS OF INTEREST

- MACH NO. DEPENDENT SHOCK WAVE ATTENUATION AND DISPERSION VS. GAS PRESSURE AND CURRENT DENSITY
- SIMULTANEOUS MULTIPOINT MEASUREMENTS
 - GAS HEATING EFFECTS
 - LINEAR/NONLINEAR ENERGY COUPLING
 - ENERGY TRANSFER MECHANISM
- ENERGY EXCHANGE MECHANISMS
 - CHARGE EXCHANGE EFFECTS
 - ELECTRON ENERGY ENHANCEMENT BY AMBIPOLAR ELECTRIC FIELD
 - KINETIC TO ELECTROSTATIC ENERGY TRANSFER

Initial Replication of Russian Results at AEDC

(0.75-in diam sphere, 30 torr)



Weakly Ionized Gas Research

Russian Ballistic Tests (G. Mishin & A. Kilmov, 1978)

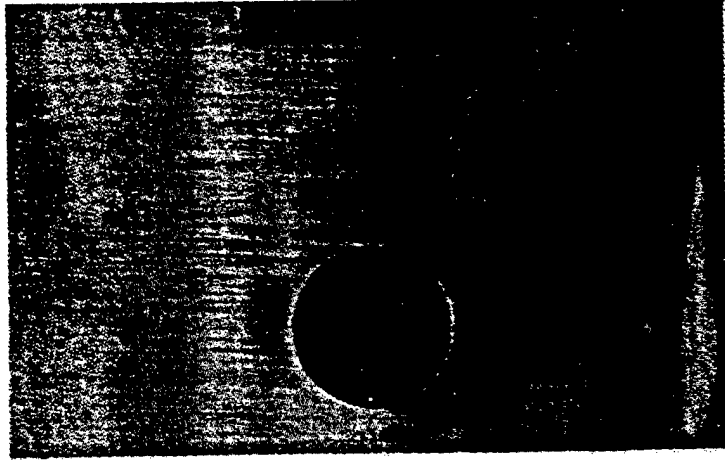
- Effect of pre-ionization on the flow around a sphere at Mach 6 in air

(a) Without Pre-ionization



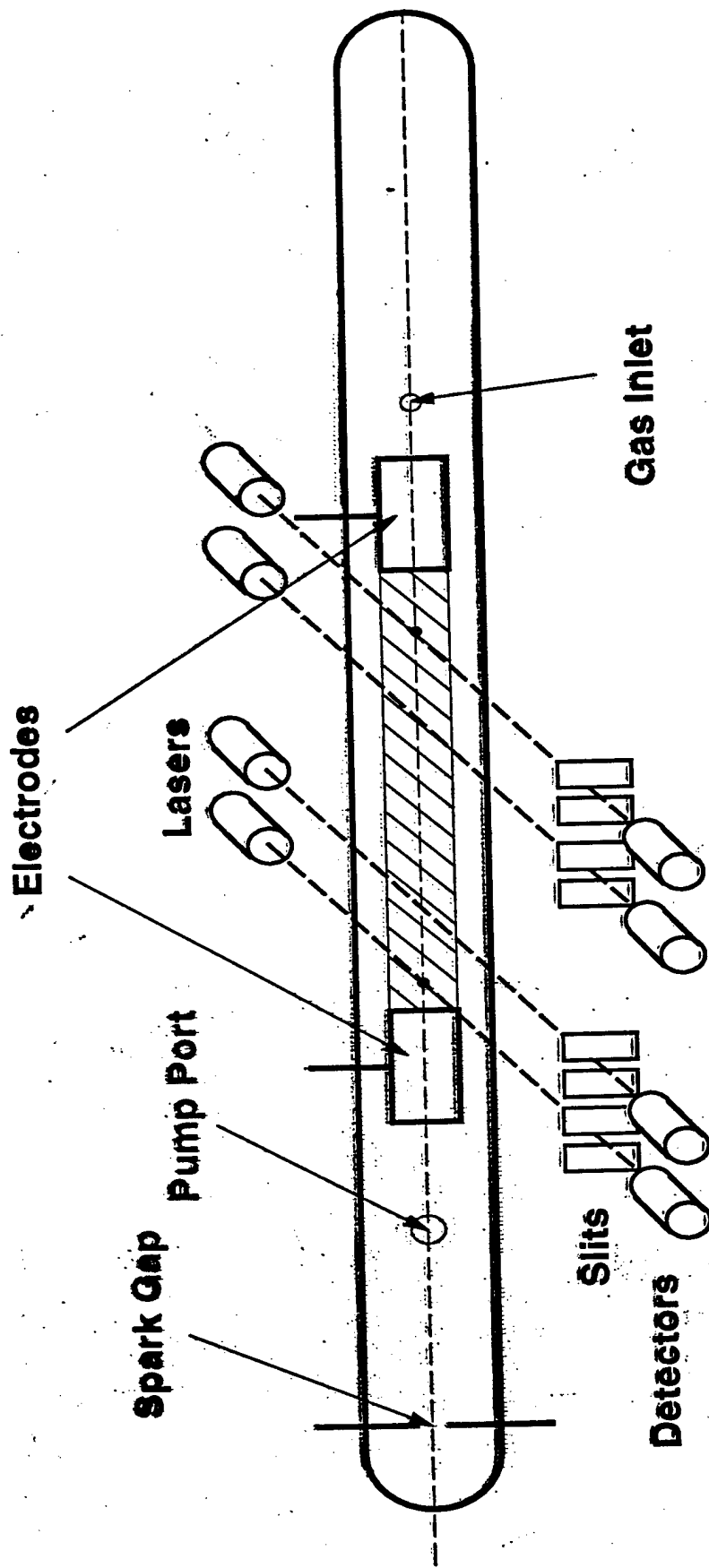
$M = 6$

(b) With Pre-ionization

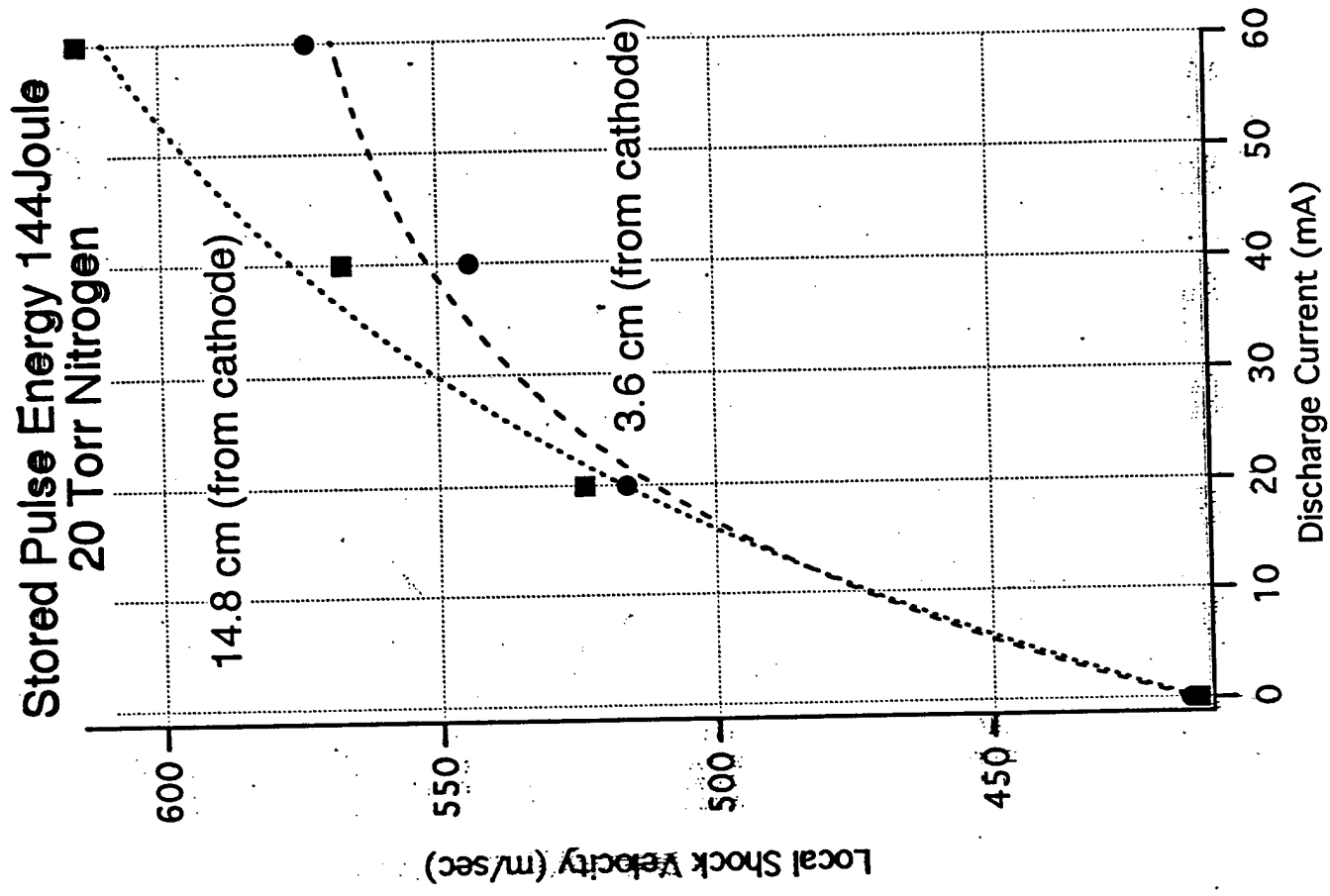
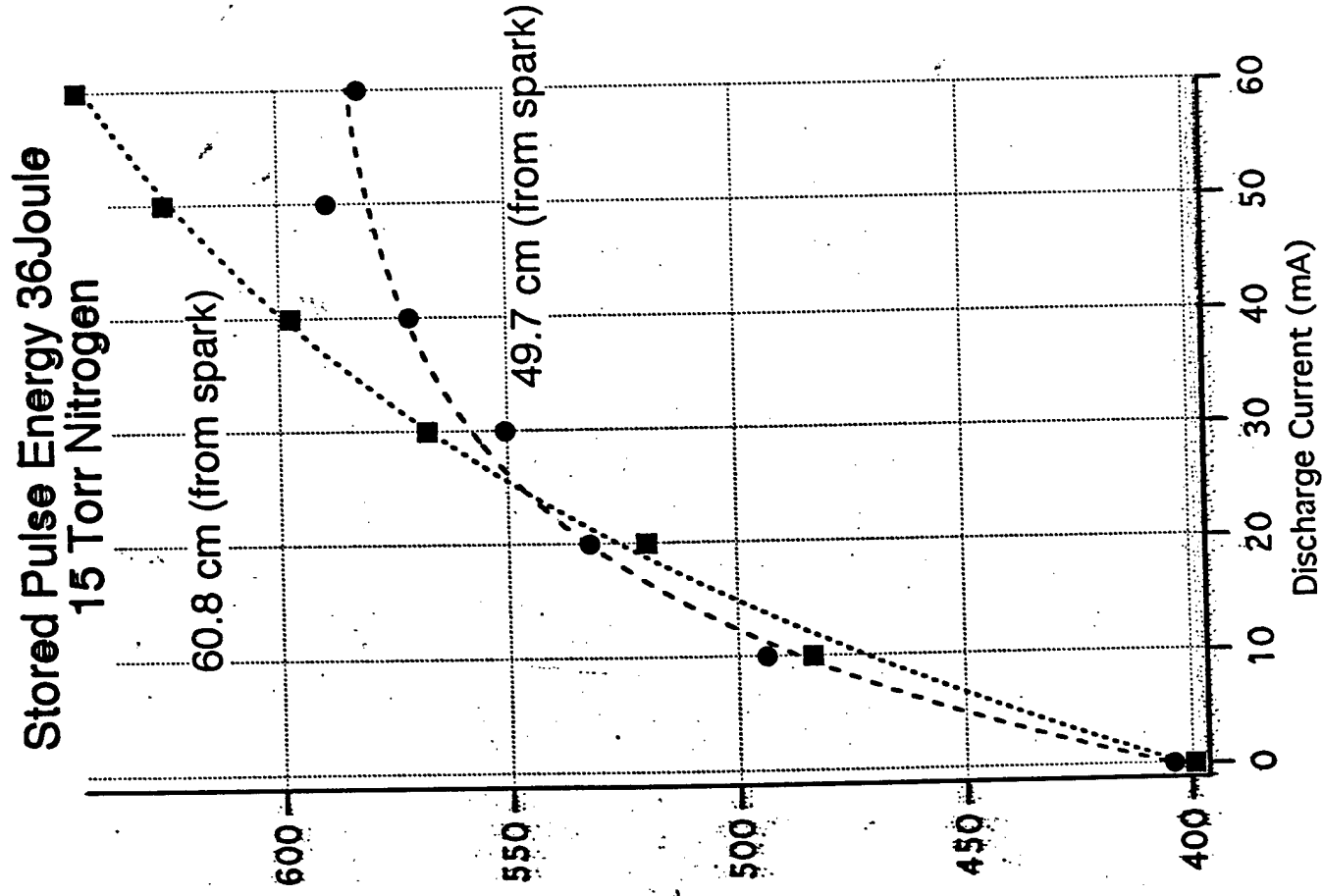


$M = 6$

Schematic of Experiment



Local Velocity in Discharge as Function of Discharge Current



SHOCK WAVE INTERACTIONS WITH WEAKLY IONIZED GASES

- Confirmed shock wave relaxation in nonequilibrium plasmas
- Occurs even at 10^{-7} fractional ionization
- Measurements demonstrated highly non-linear interactions of acoustic shock wave with non-equilibrium weakly ionized plasmas
- Measurements need to be performed to quantify interaction mechanisms and energy balance
- Data will be required to permit energy efficiency analysis of plasma based drag reduction and shock wave amplitude control

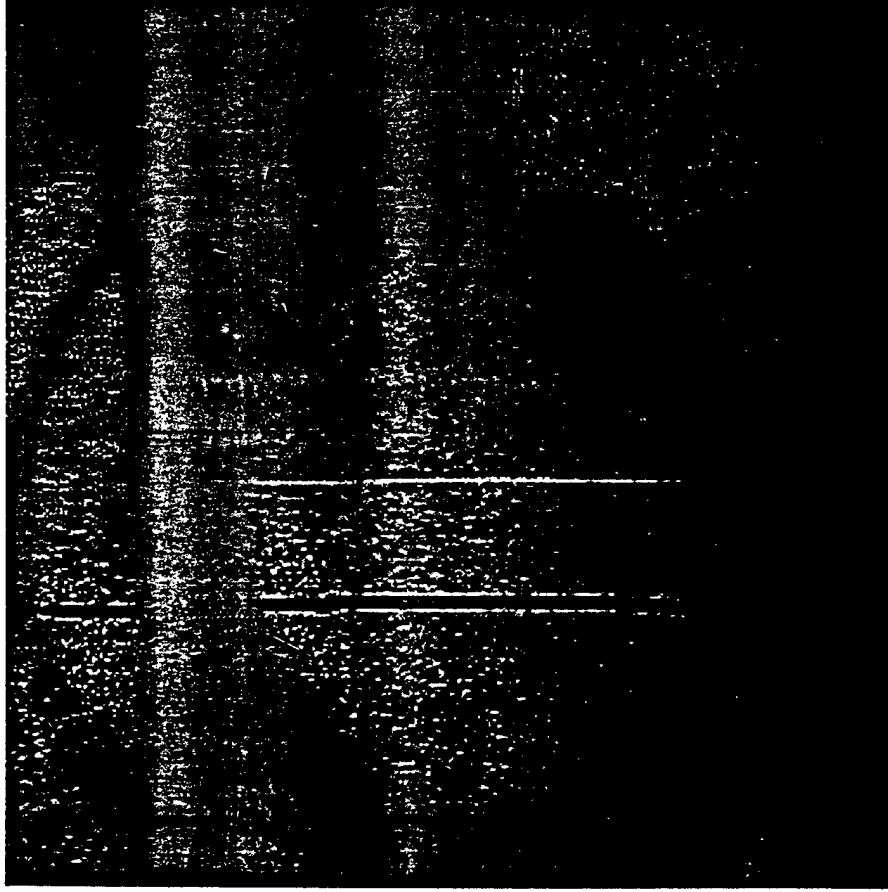
OUR PLANNED RESEARCH FOR FY98-99

- Simultaneous multi-point local shock wave velocity measurements.
- Spectroscopic measurement of gas temperatures.
- Shock wave structure recovery in decaying plasma and neutral gas.
- 2-D Schlieren imaging of shock profiles.
- Spectroscopic measurement of shock wave density profile.
- Shock dispersion measurements in pulsed and radio frequency discharges.
- Shock propagation in double layer plasmas.
- Shock induced electric field modulation measurements.

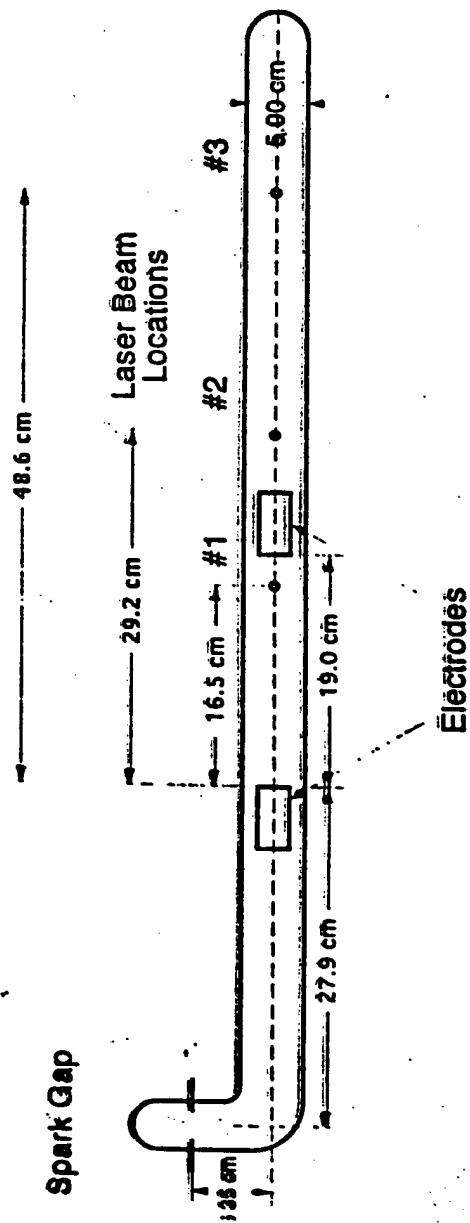
SUMMARY

- Data show the dissipation of supersonic shock waves is nonlinearly dependent on amplitude in weakly ionized nonequilibrium plasmas
- Spatially resolved measurements indicate that shock propagation velocity change and dispersion cannot be explained by gas heating only
- Shock wave dispersion and damping are dependent on the gas number density and fractional ionization
- The energy coupling mechanisms are not understood at present
- Plasma energy density and single particle collision frequency are inadequate to explain the observed phenomena
- Long range cooperative interactions may be important

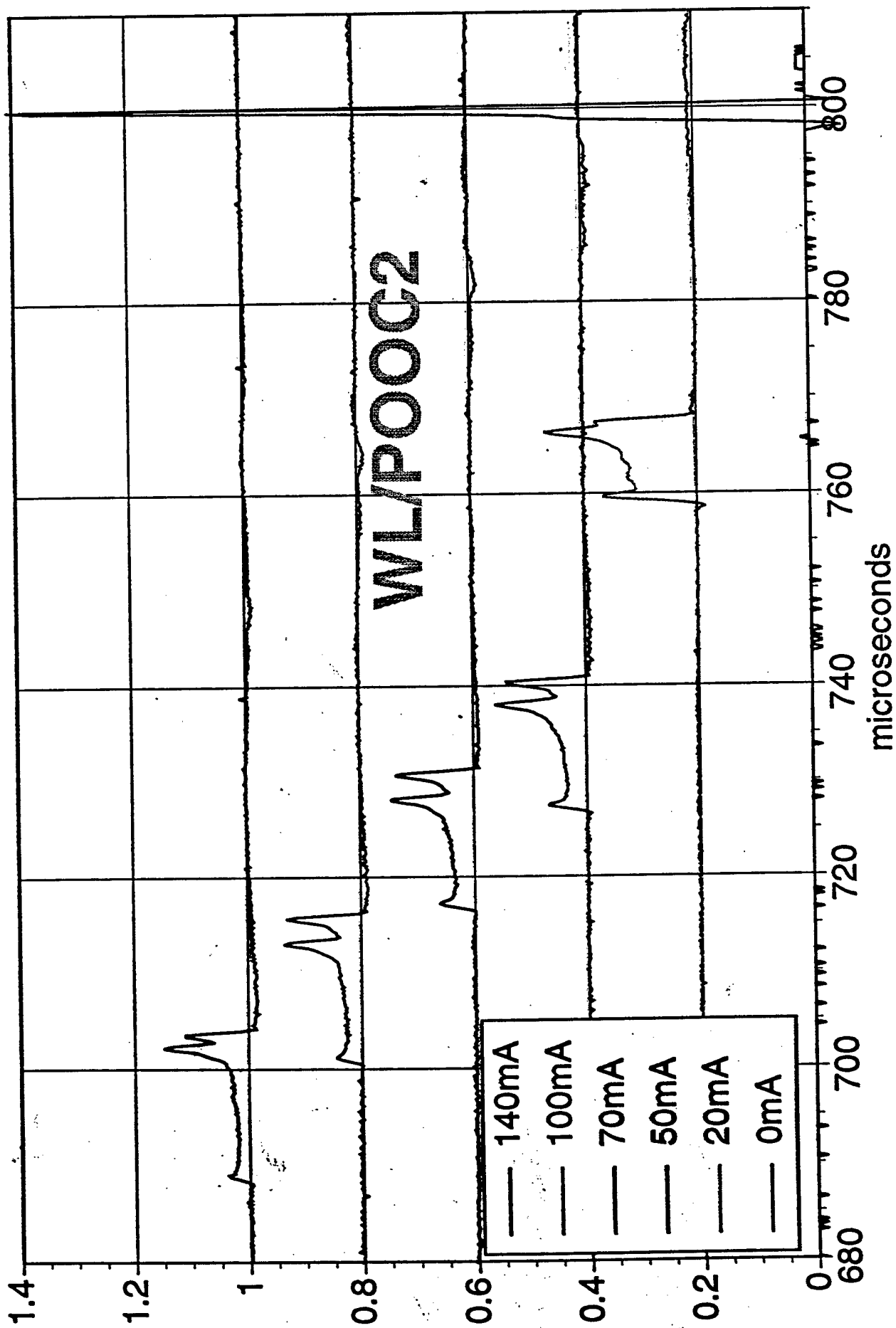
A Comparison of the Shock Thickness With a 0.8 mm
Diameter Wire , 30 Torr Argon , Pulser Voltage 9kV



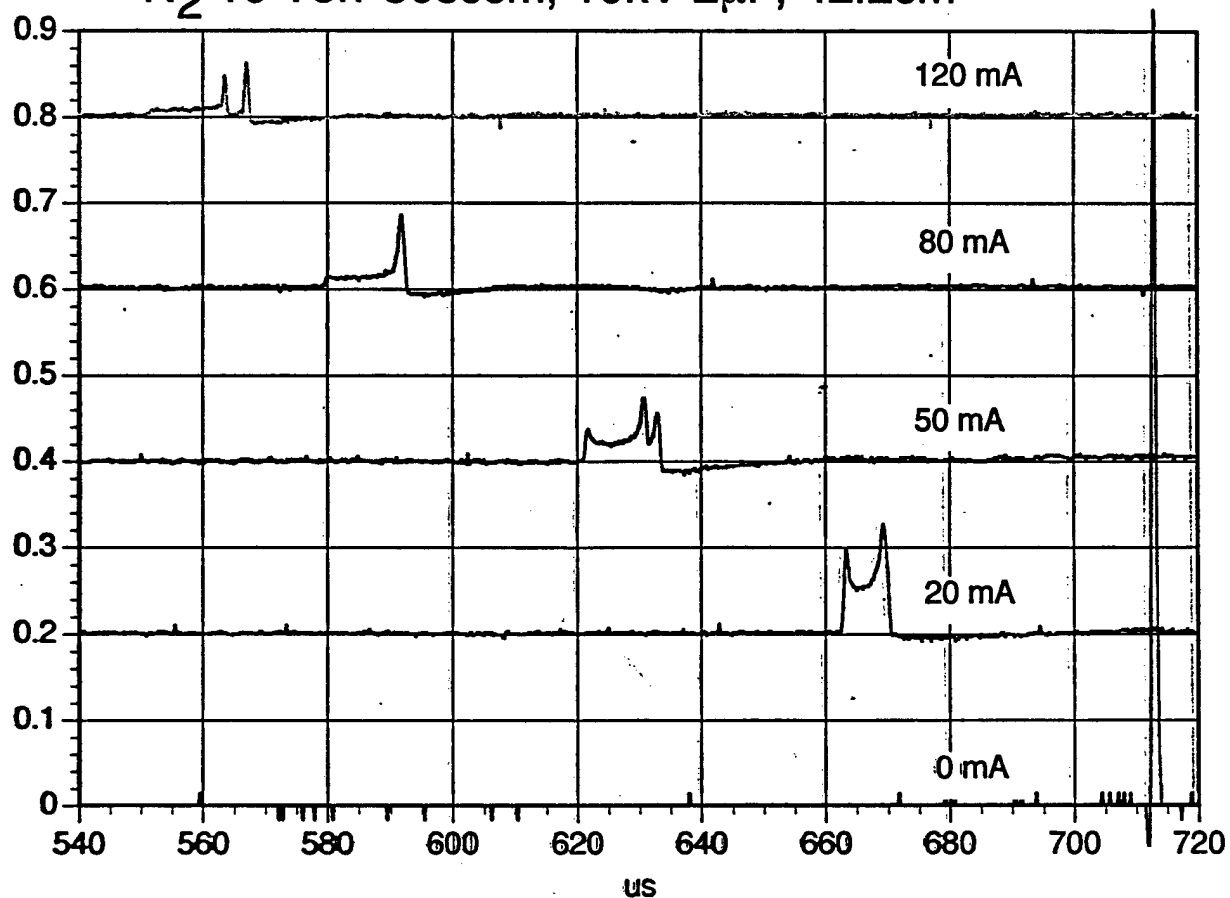
Discharge Tube Dimensions and Location of Laser Beams



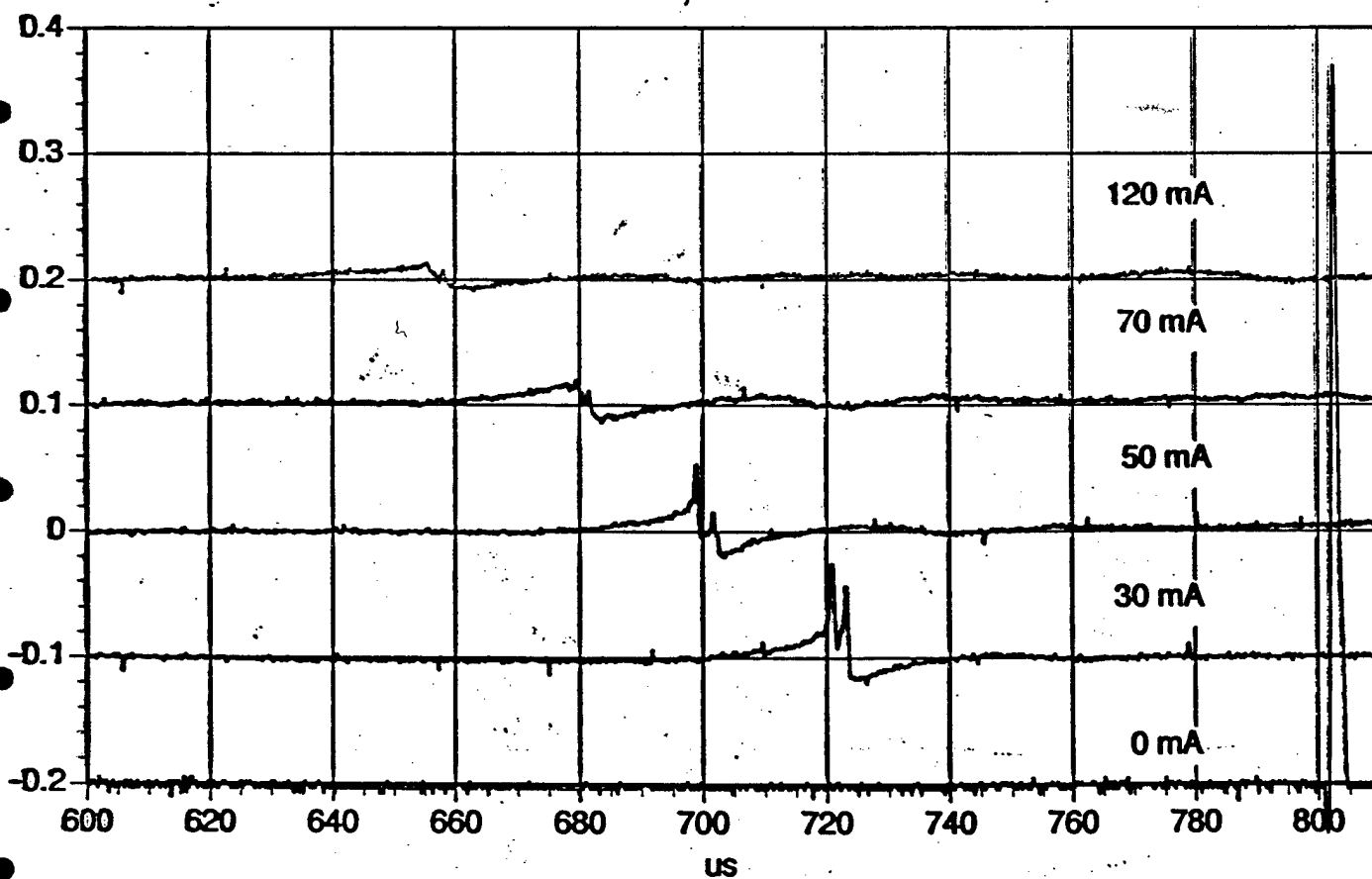
Argon 30 Torr, 10kV 2 μ F, 42.2cm



N₂ 10 Torr 50sccm, 10kV 2 μ F, 42.2cm



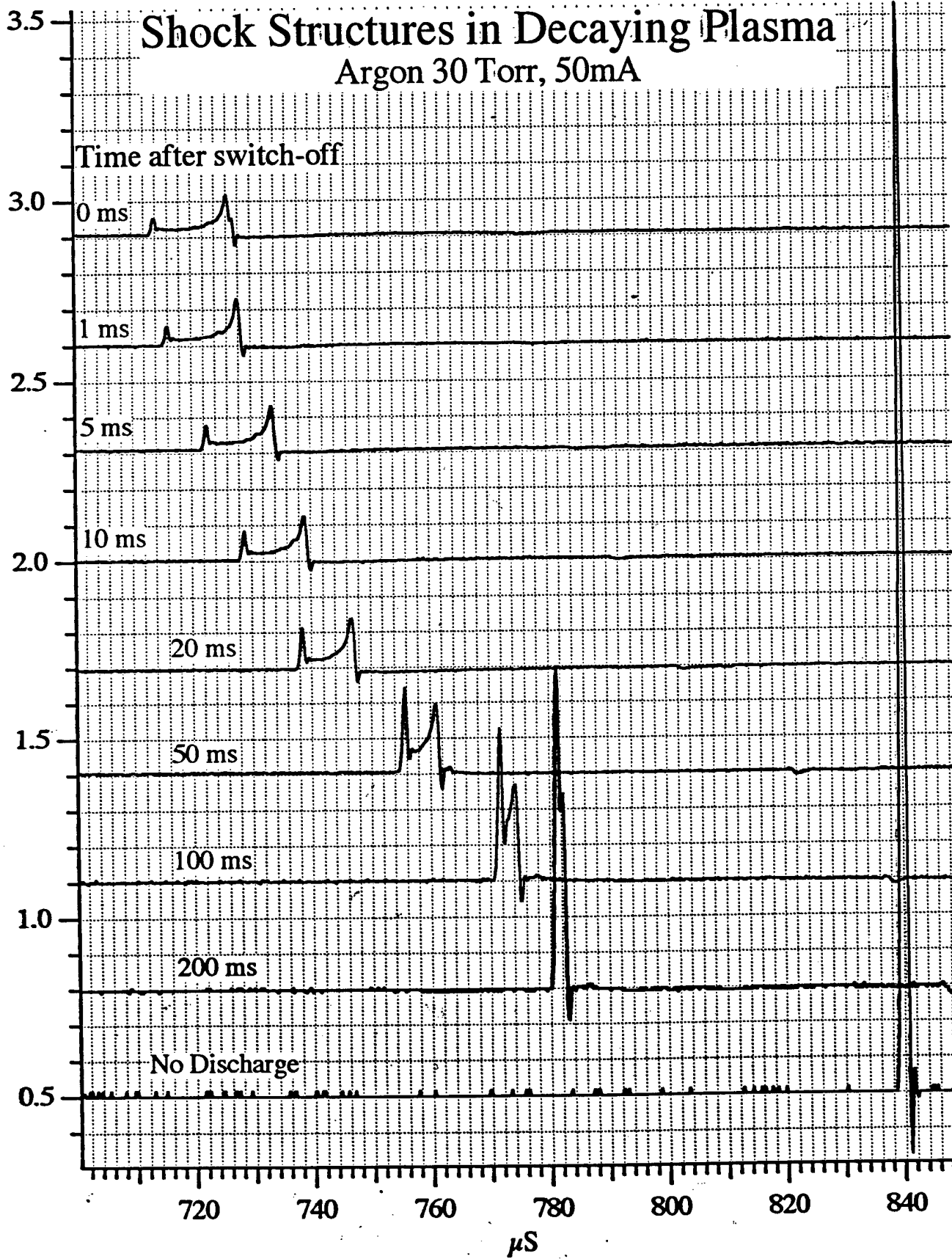
50 Torr, 42.2cm

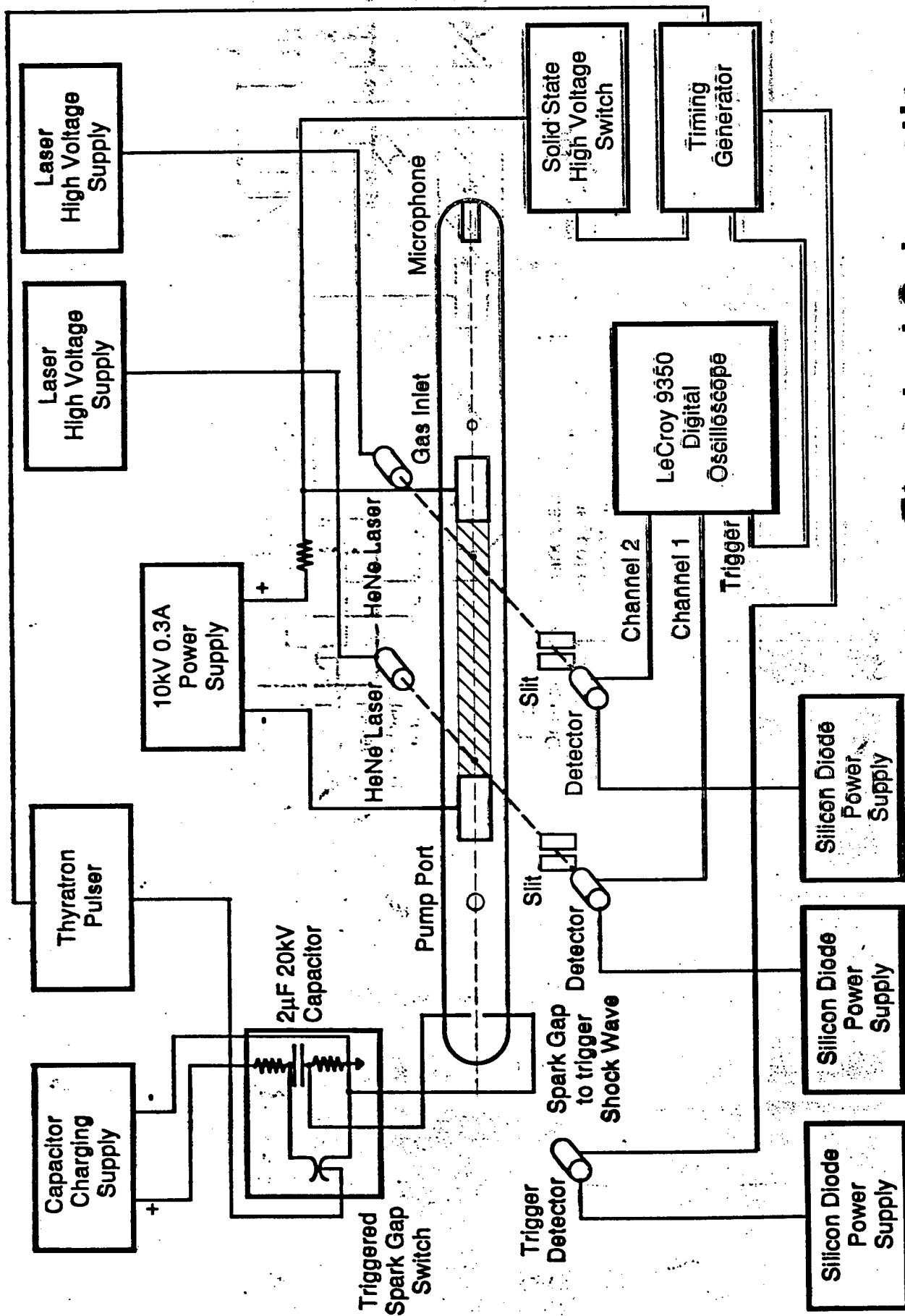


Shock Structures in Decaying Plasma

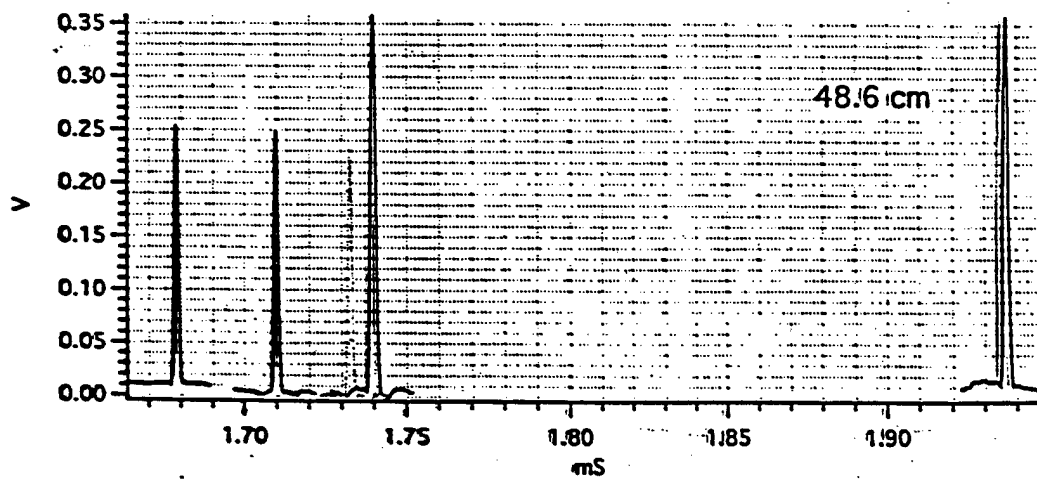
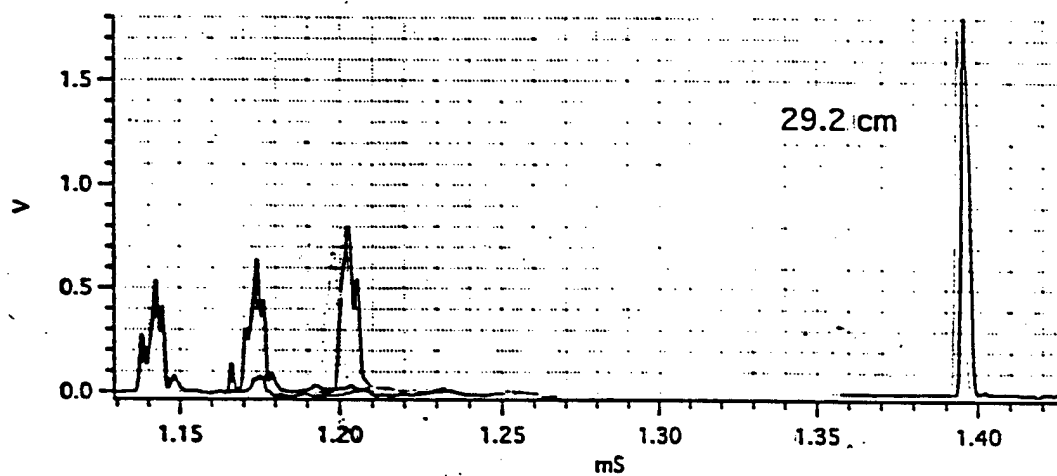
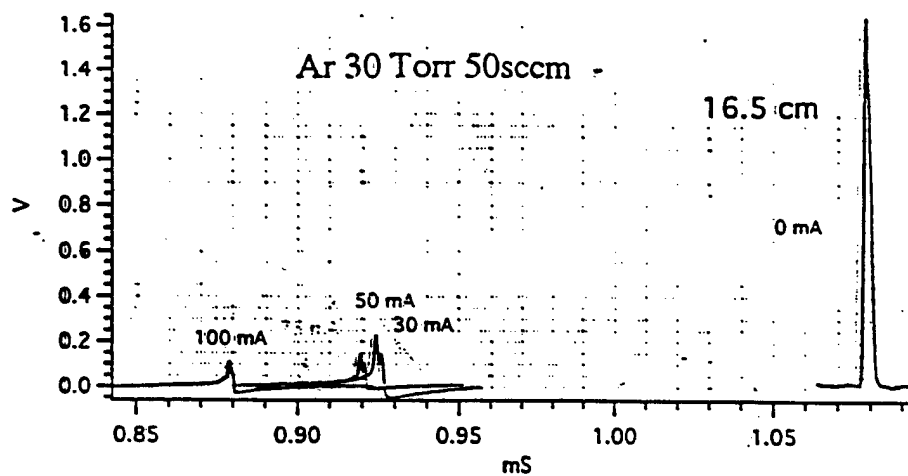
Argon 30 Torr, 50mA

Time after switch-off

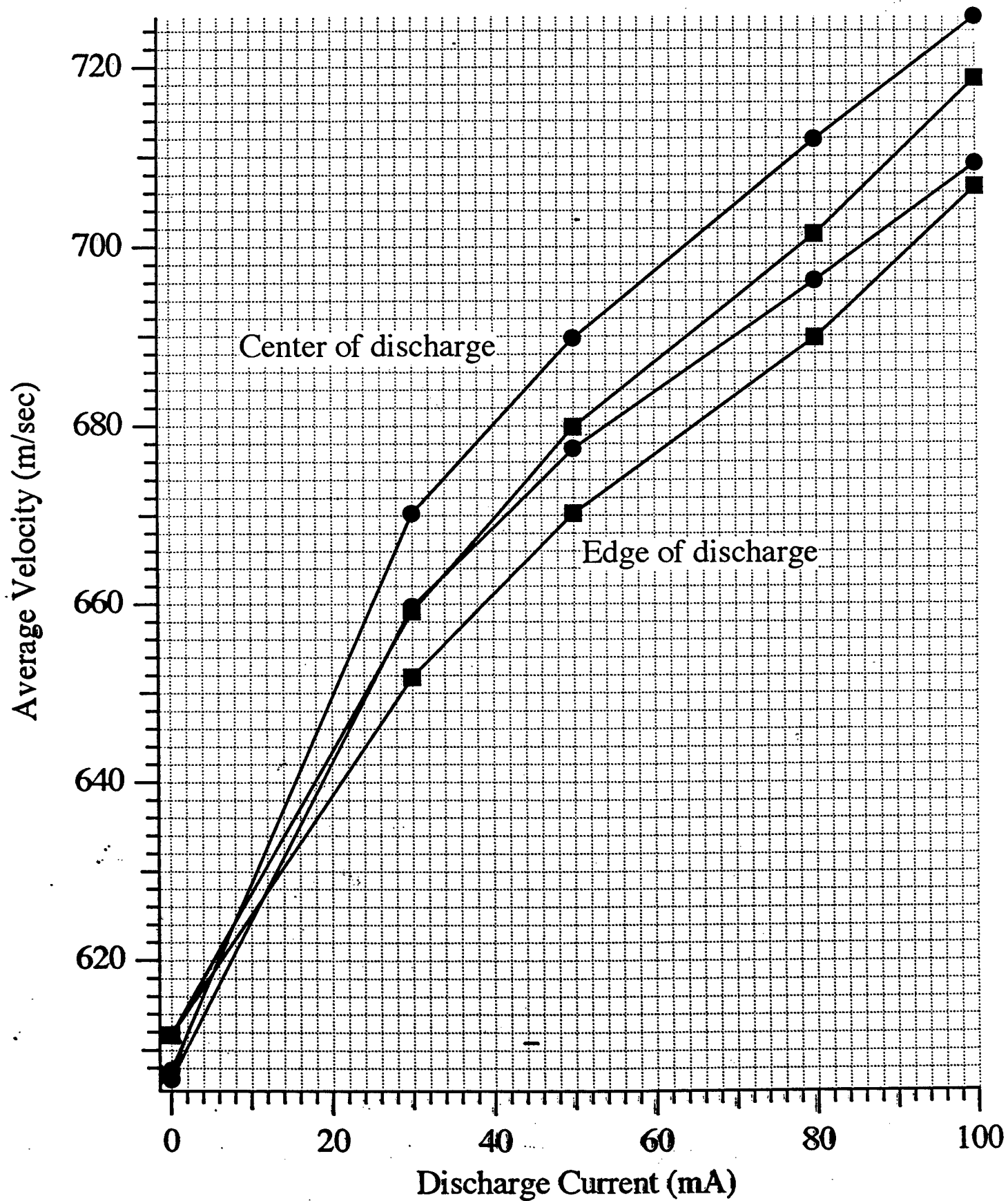




Electrical Schematic
for typical measurement



Average Velocity of Front and Back Boundaries
of Shockwave at Center and Off-Axis
as Function of Discharge Current

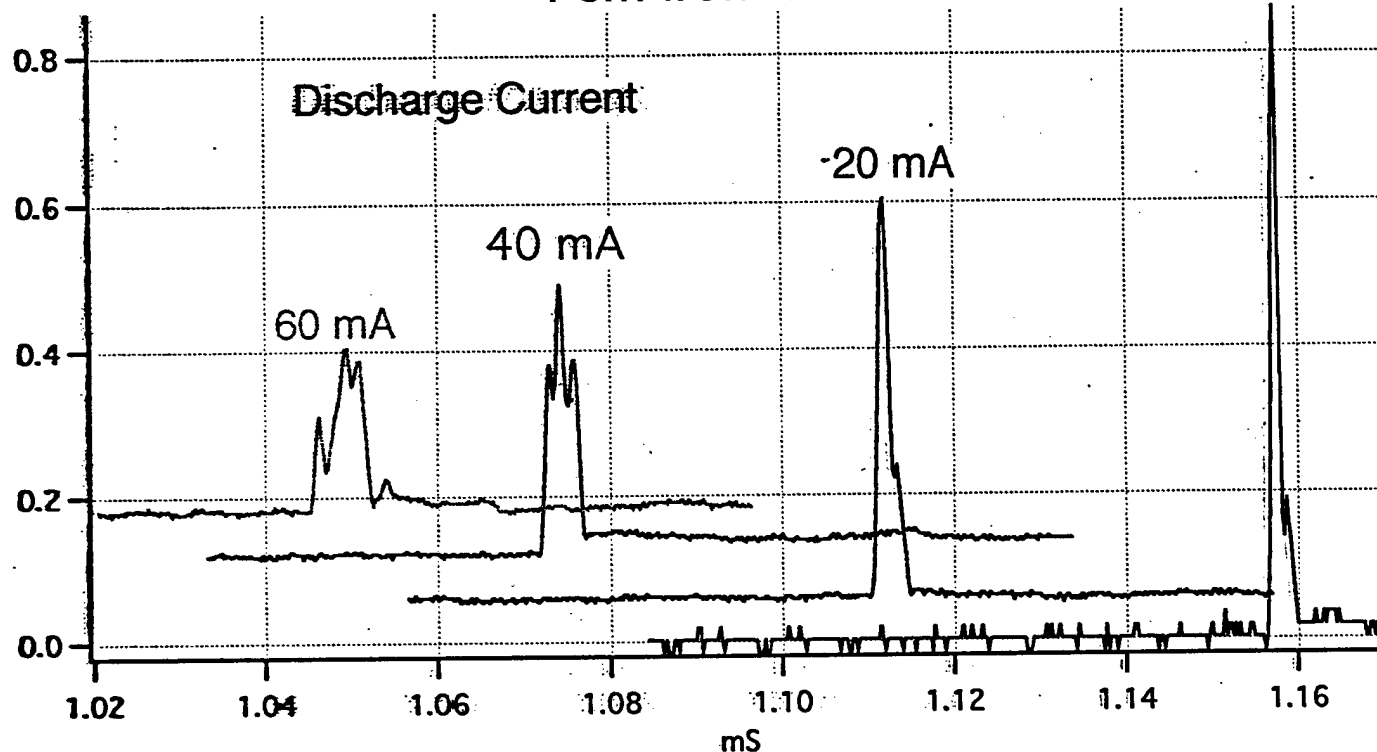


Deflection Signals Downstream of Discharge

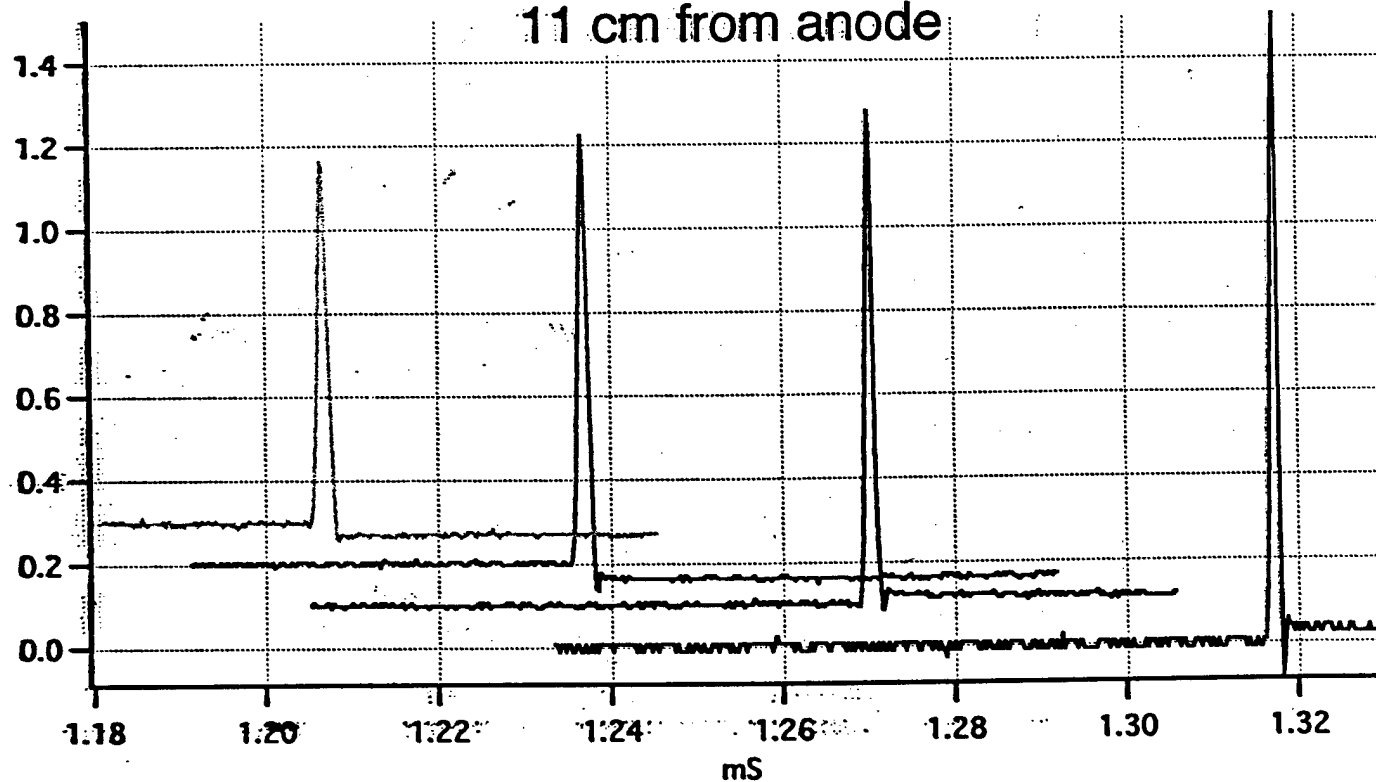
Pulse Energy 81 Joule

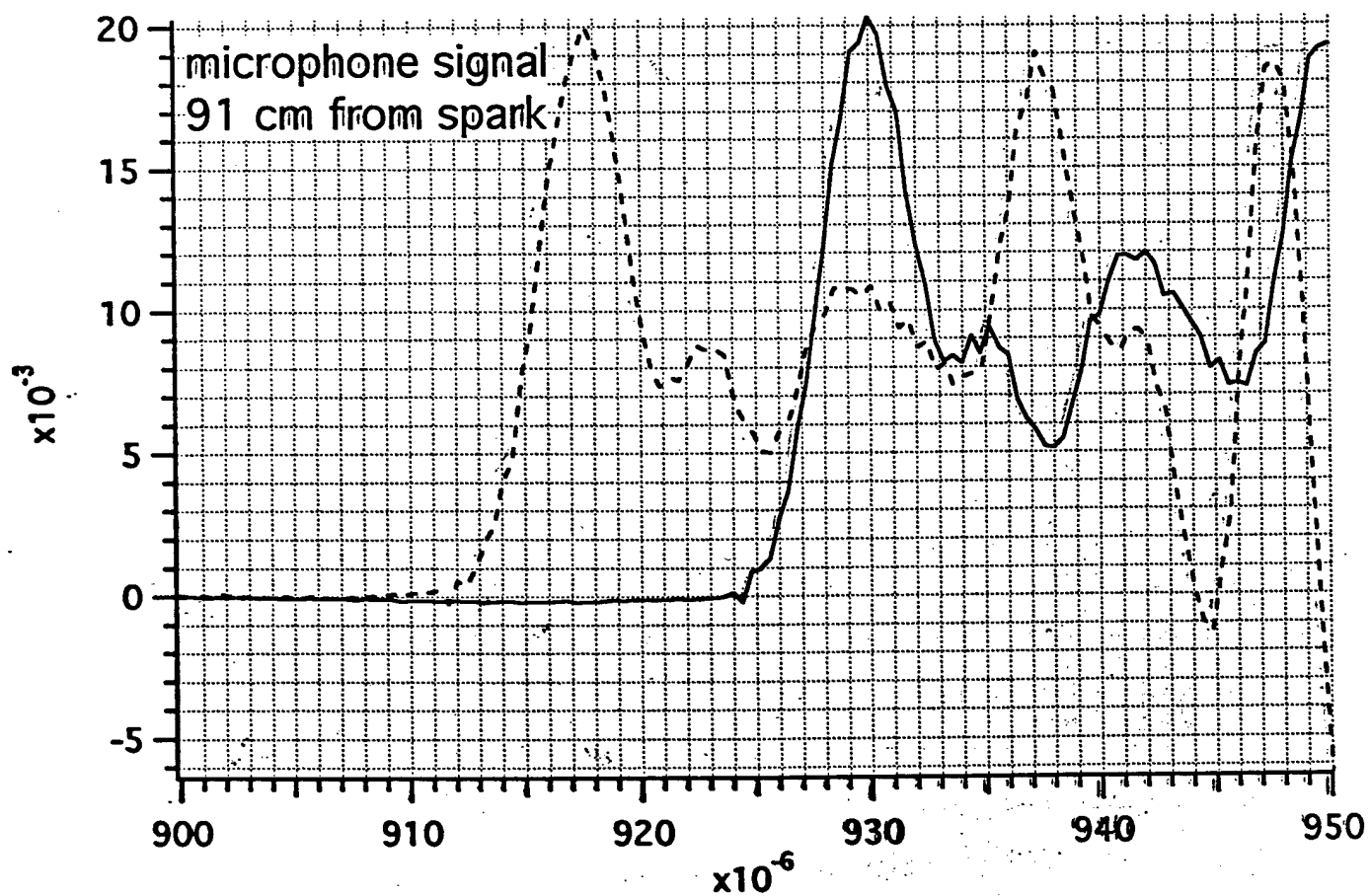
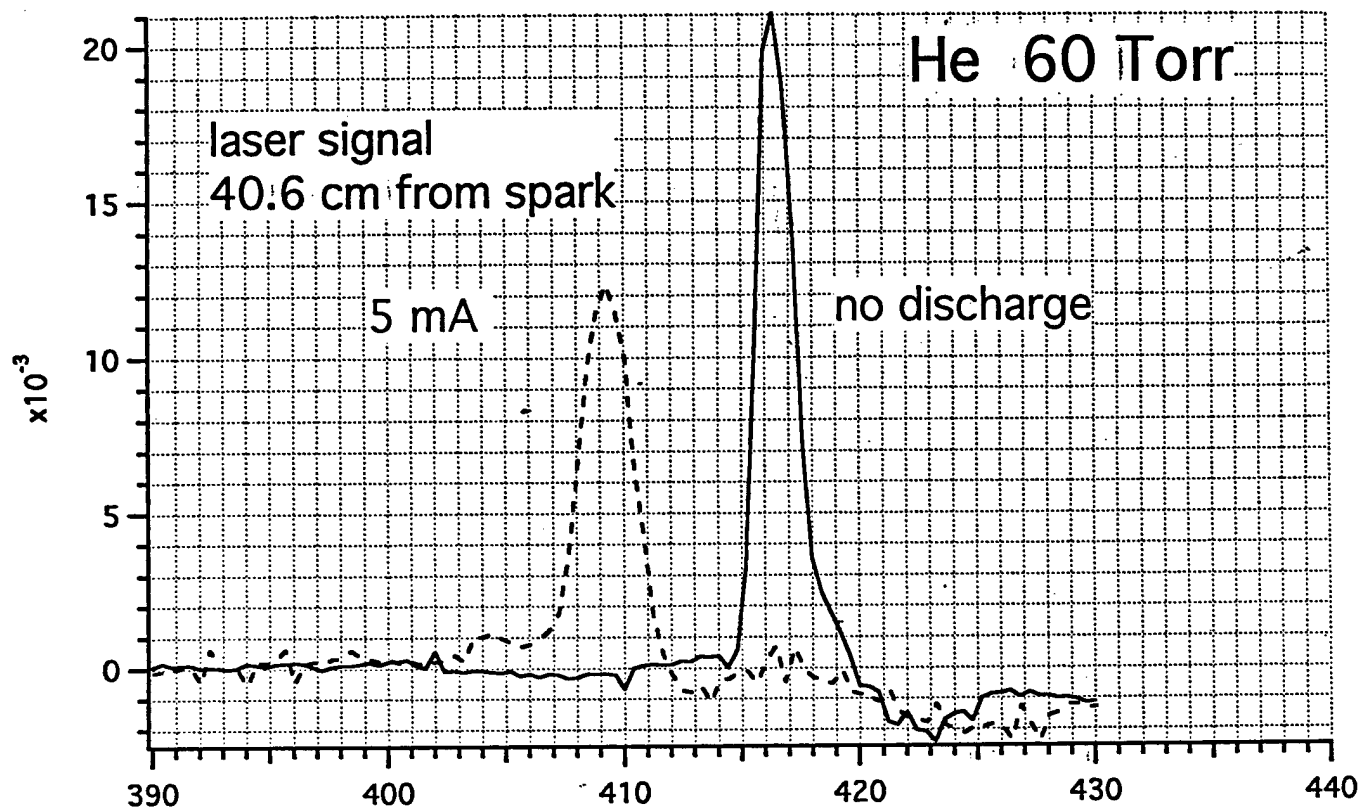
4 cm from anode

0 mA



11 cm from anode





**UNDERSTANDING AND CONTROL OF IONIZED
HIGH-SPEED FLOWS**

**AFOSR WORKSHOP
PRINCETON UNIVERSITY
FEBRUARY 26-27, 1998**

**Plasma Drag Reduction — An Overview of the Issues
Aaron Auslender
NASA Langley Research Center**

OUTLINE

- Problem Statement and Related Issues
- Present Research Focus — NASA/LaRC and ICASE
- Analysis of Air Force Experiments — ODU
- Ballistic Range Mechanisms — ODU
- Onboard-Microwave Experiments — NASA/LaRC
- Shock Tube Experiments — FA&M

Flow around a sphere moving supersonically in a gas-discharge plasma

G. I. Mishin, Yu. L. Serov, and I. P. Yavor

(Submitted April 11, 1991)

Pis'ma Zh. Tekh. Fiz. 17, 65-71 (June 12, 1991)

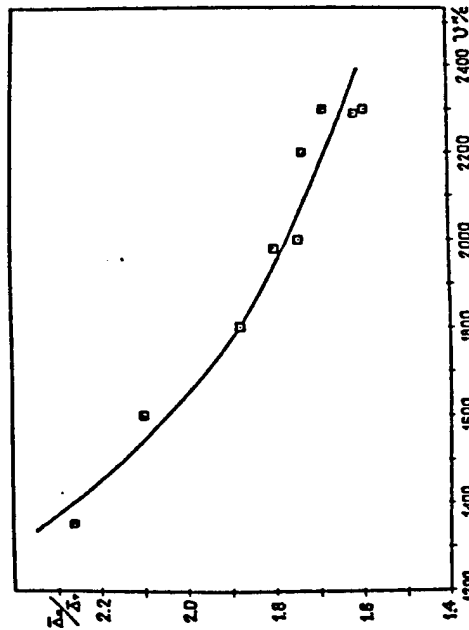


FIG. 2. Ratio of experimentally determined relative standoff distance of the bow shock from a sphere moving through a glow-discharge plasma to the corresponding calculated value of the relative standoff distance in air at the same temperature as the plasma ($\bar{\Delta}_p$ is the relative standoff distance of the bow shock in the plasma, $\bar{\Delta}_a$ is the relative standoff distance in air at $T = 1350$ K, and v is the velocity of the sphere).

414 Sov. Tech. Phys. Lett. 17(6), June 1991

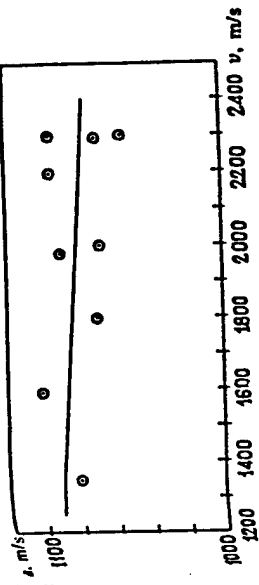
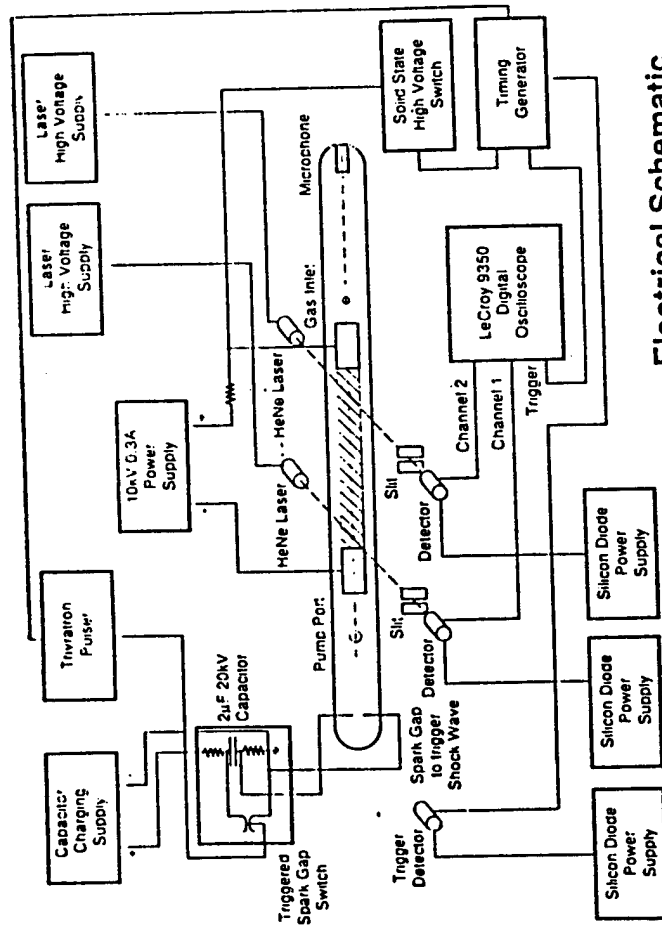
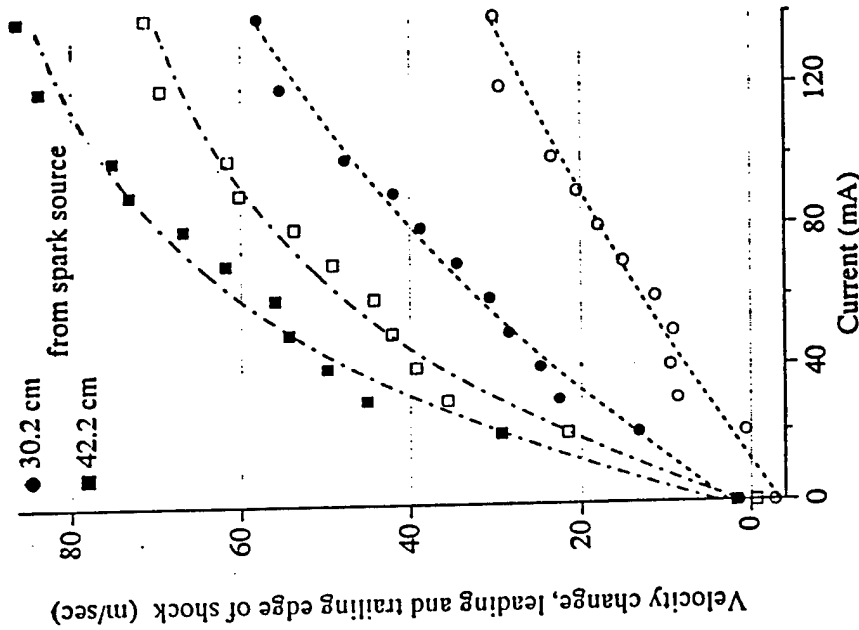


FIG. 3. "Effective" (governing the flow pattern) sound velocity in a plasma in the range of velocities of a spherical model 1350-1300 m/s (a is the effective sound velocity, and v is the velocity of the sphere).

The main series of experiments was carried out in a steadily burning discharge at a gas pressure of 40-50 torr and a discharge current density of 25-50 mA/cm². The electron density was $\approx 10^{11}$ - 10^{12} cm⁻³, the ionization coefficient was $\alpha = 10^{-5}$ - 10^{-6} , and the electron temperature was $T_e = 1$ -4 eV. The gaseous temperature T_g of the plasma was determined by several techniques: by measuring the density of the gas from interferograms, by means of Chromel-Alumel thermocouple, by radiation pyrometry, and from the electron vibration-rotation spectra of the molecules.² The measurements showed that the temperature distribution along the diameter is bell-shaped, with $T_g \leq 1400$ K on the axis of the discharge.

• no shock case(3)



ACOUSTIC SHOCK WAVE PROPAGATION IN NONEQUILIBRIUM NITROGEN AND ARGON PLASMAS

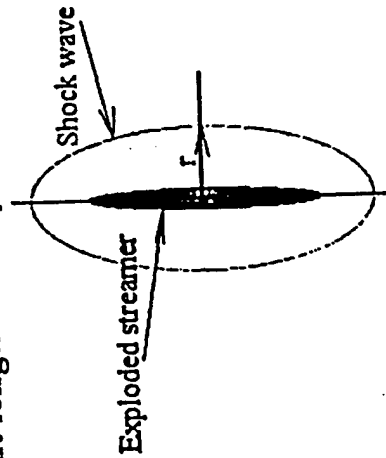
B. N. GANGULY AND P. BLETZINGER
WRIGHT LABORATORY, WRIGHT-PATTERSON AFB

**Physics of the
Undercritical Microwave Discharge
and Its Influence on the
Supersonic Aerodynamics and
Shock Waves**

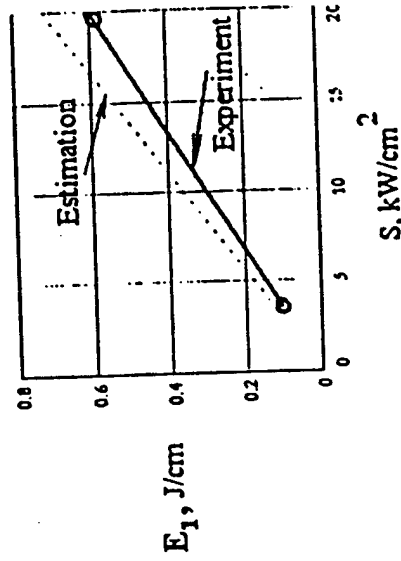
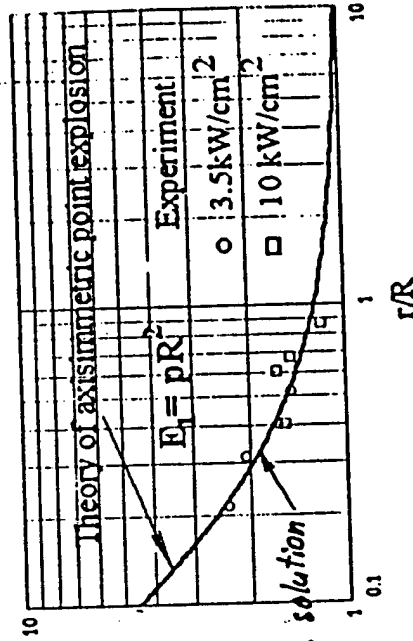
K. Khodataev (MRTI)

Absorption Ability of the Microwave Streamer Discharge

Each filament element (streamer) being heated by microwave radiation explodes and generates the shock wave. The phase trajectory $M(r)$ of the shock wave gives the energy absorbed by filament length unit E_1



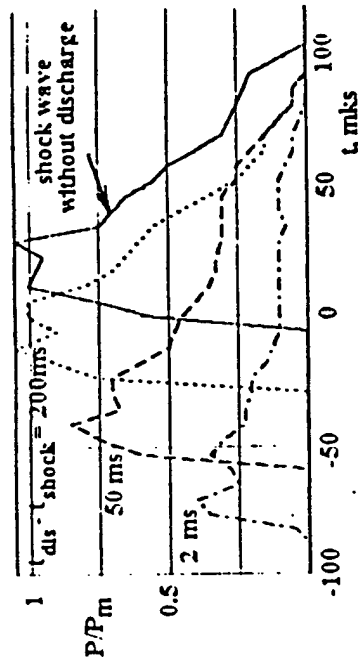
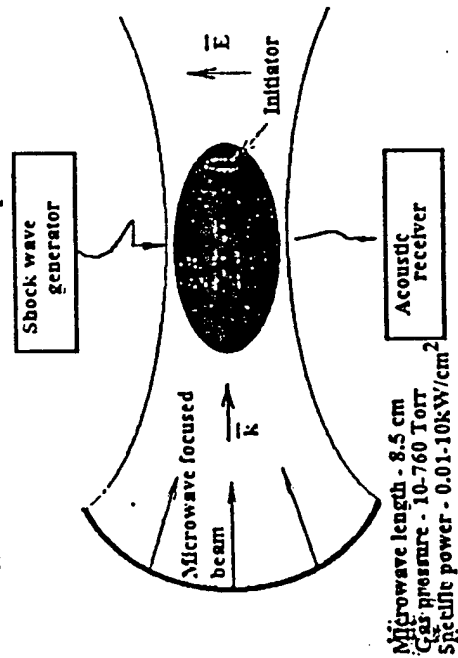
Sedov's solution



The net of the microwave discharge filaments absorbs whole radiation flux.

The Experimental Data about a Shock Wave Attenuation in a Microwave Discharge

The scheme of the experiment



$p = 30 \text{ Torr}$

The typical oscillograms

The measurements show that discharge region:

- attenuates the pulse shock waves,
- increases the pulse shock wave time duration,
- the memory time of discharge region equals more than 0.1 s.

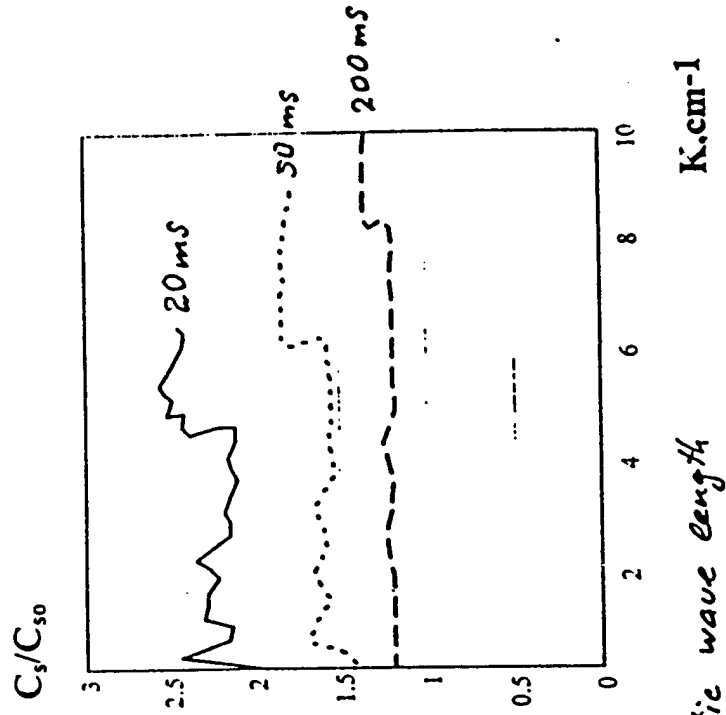
The Acoustic Interferometry Study of the Microwave Discharge Region

The sound velocity dependence on wave number $C_s(k)$ in the decaying microwave discharge plasma.

The delay time after discharge: 20 ms - solid, 50 ms - dot, 200 ms - dash line.

The dependence show that:
the discharge region

- *is heated in average,*
- *has microscale hot inhomogeneties,*
- *has a memory time up to 0.2s.*



$$K = \frac{2\pi}{\lambda} \quad - \text{acoustic wave length}$$

K.cm^{-1}

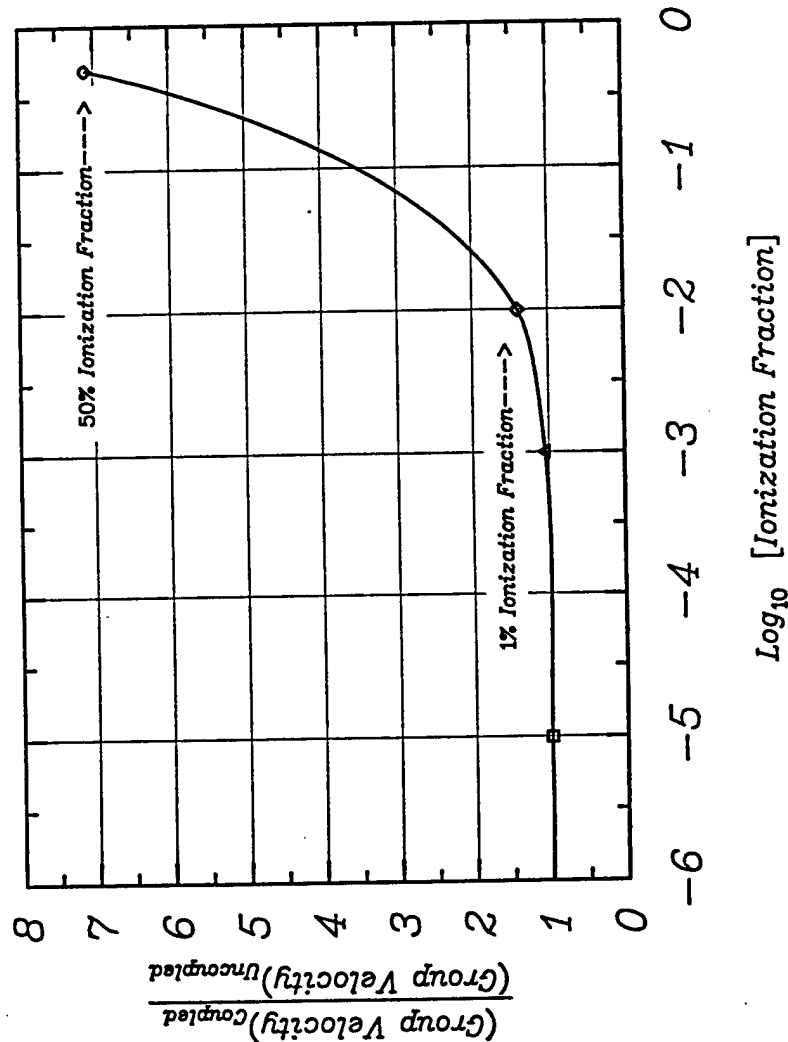
$$\begin{aligned}
 \frac{\partial v_n}{\partial t} &= -c_n^2 \nabla \rho_v / \rho_{0v} - \omega_{ni} (v_n - v_i) \\
 \frac{\partial \rho_v}{\partial t} &= -\rho_{0v} \nabla \cdot v_n \\
 \frac{\partial v_i}{\partial t} &= -c_i^2 \nabla \rho_u / \rho_{0u} - \omega_{in} (v_i - v_n) \\
 \frac{\partial \rho_u}{\partial t} &= -\rho_{0u} \nabla \cdot v_i
 \end{aligned}
 \tag{1}$$

$$\begin{aligned}
 v_n &= \nabla \phi_n \\
 v_i &= \nabla \phi_i
 \end{aligned}
 \tag{2}$$

$$\begin{aligned}
 \frac{\partial^2 \phi_n}{\partial t^2} - c_n^2 \nabla^2 \phi_n + \omega_{ni} \left(\frac{\partial \phi_n}{\partial t} - \frac{\partial \phi_i}{\partial t} \right) &= 0 \\
 \frac{\partial^2 \phi_i}{\partial t^2} - c_i^2 \nabla^2 \phi_i + \omega_{in} \left(\frac{\partial \phi_i}{\partial t} - \frac{\partial \phi_n}{\partial t} \right) &= 0
 \end{aligned}
 \tag{3}$$

$$\left| \begin{array}{cc} -\omega^2 + c_n^2 k^2 - i\omega\omega_{ni} & i\omega\omega_{ni} \\ i\omega\omega_{in} & -\omega^2 + c_i^2 k^2 - i\omega\omega_{in} \end{array} \right| = 0
 \tag{4}$$

- Analysis assumed:
 - (1) Uncoupled Speed-of-Sound Ratio "Fast-Wave" to the "Slow-Wave" equals ten
 - (2) Ionization Fraction is constant
- Conclusion:
 - (1) "Slow-Wave" only propagates in the long-wave-length limit
 - (2) Large Ionization Fractions are required ("Slow-Wave")



PRESENT RESEARCH EFFORTS

- Kinetics
 - Excited State \rightarrow reactions \rightarrow "hot" electron production
 - Metastable States \rightarrow "long-lived" neutrals
- Far-From Equilibrium Effects \rightarrow neutral particle stationary solutions of the Boltzmann kinetic equation having sources/sinks (fluxes)
 - \rightarrow influences speed-of-sound
 - \rightarrow yields mass/momentum/energy fluxes in the shock region (OSU)
- Far-From Equilibrium Effects (OSU, NASA/LaRC and ICASE)
 - DSMC Modelling (NASA/LaRC and ICASE) employing a central forcing function of the class: $Force = \alpha_0 e^{-(X-X_{SHOCK})^2/\alpha_1}$ to assess the magnitude of the required mechanism(s)
 - Development of related mechanism(s) and analysis of the relevant "fluid" equation set (OSU)

Shock-Wave Structure in a Rigid Sphere Gas¹

G. A. BIRD²
Department of Mechanics of Fluids, University of Manchester, Manchester, England

Translational Equilibrium in a Rigid Sphere Gas

G. A. Bird
*Department of Aeronautical Engineering, University of Sydney,
 Sydney, Australia*
 (Received 10 May 1963)

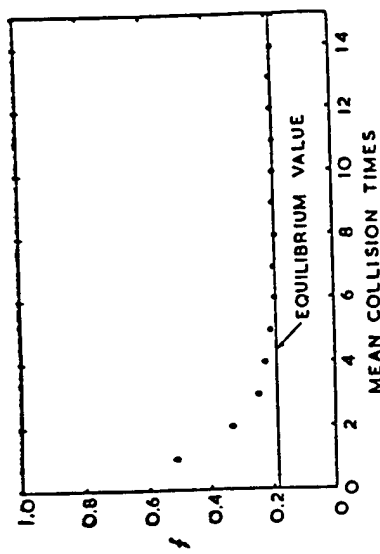


FIG. 2. Fraction of molecules in range 0.9 to 1.1 v_x .

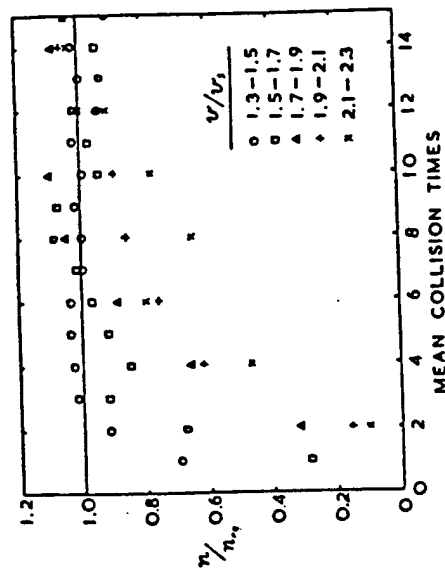
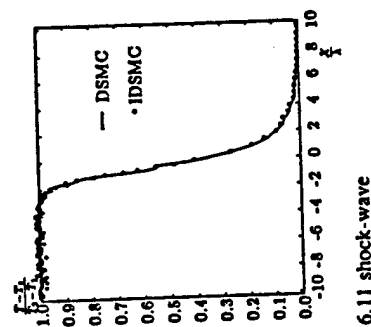


FIG. 3. Approach to equilibrium in higher speed ranges.



Exact power-law solutions of the particle kinetic equations

A. V. Kats, V. M. Kontorovich, S. S. Moiseev, and V. E. Novikov

*Khar'kov Research Institute for Metrology,
 Institute for Radiophysics and Electronics, Ukrainian Academy of Sciences,
 and Physico-technical Institute, Ukrainian Academy of Sciences*
 (Submitted November 21, 1975)
 Zh. Eksp. Teor. Fiz. 71, 177-192 (July 1976)

ODU Research Activity

- Analysis of planar-wave experiments
 - shock front propagation
- Analysis of ballistic range experiments
 - standoff distance
- Determination of underlying physical mechanisms
 - distribution of internal energy
 - collisional dynamics during relaxation
 - influence of double electric layer on charged and excited particles
 - nonequilibrium effects
- Shock dispersion experiments and plasma generation
(future work)

“Anomalous” Effects in Atomic & Molecular Gases at $T_e \gg T_n$

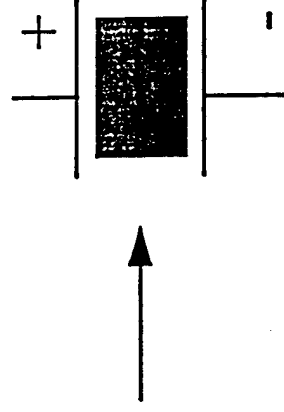
- Not observed at $T_e = T_n$.
- Not dependent on direction of applied electric field.
- Reduced/nonexistent at transverse magnetic field of below/above ~ 500 G.
- Increase with ultraviolet irradiation.
- Rise-time from plasma inception ~ 100 μ s.
- Afterglow decay time depends on gas species.
Can be > 100 ms.

Generic Experiments

- A. Shock wave propagation through a DC glow discharge

A.1.

1. parallel-plate



transverse propagation

2. cylindrical

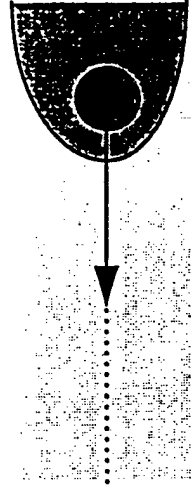
coaxial propagation

A. 2.

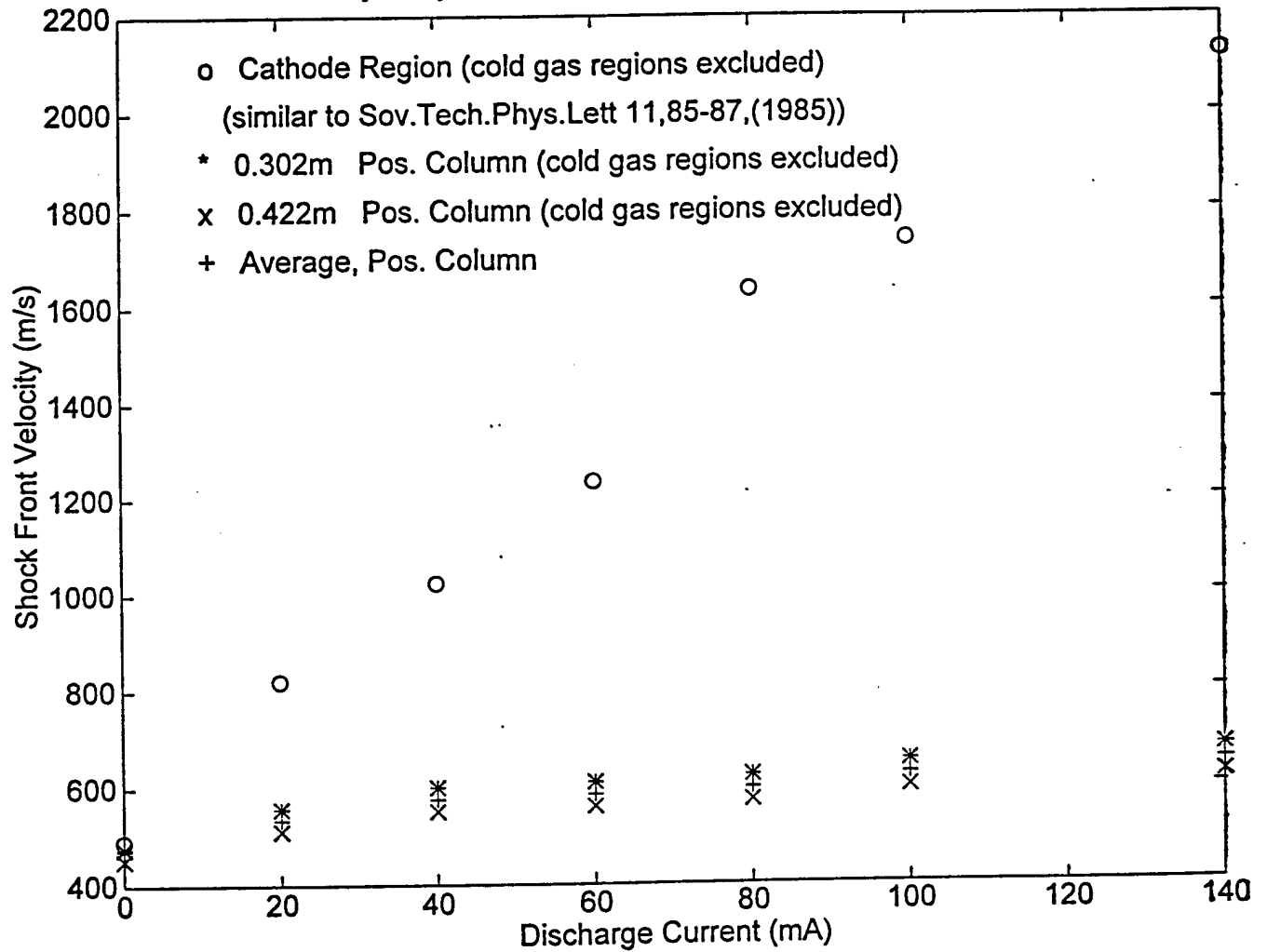


- B. Supersonic flow in weakly ionized gas around a spherical model (ballistic range experiments)

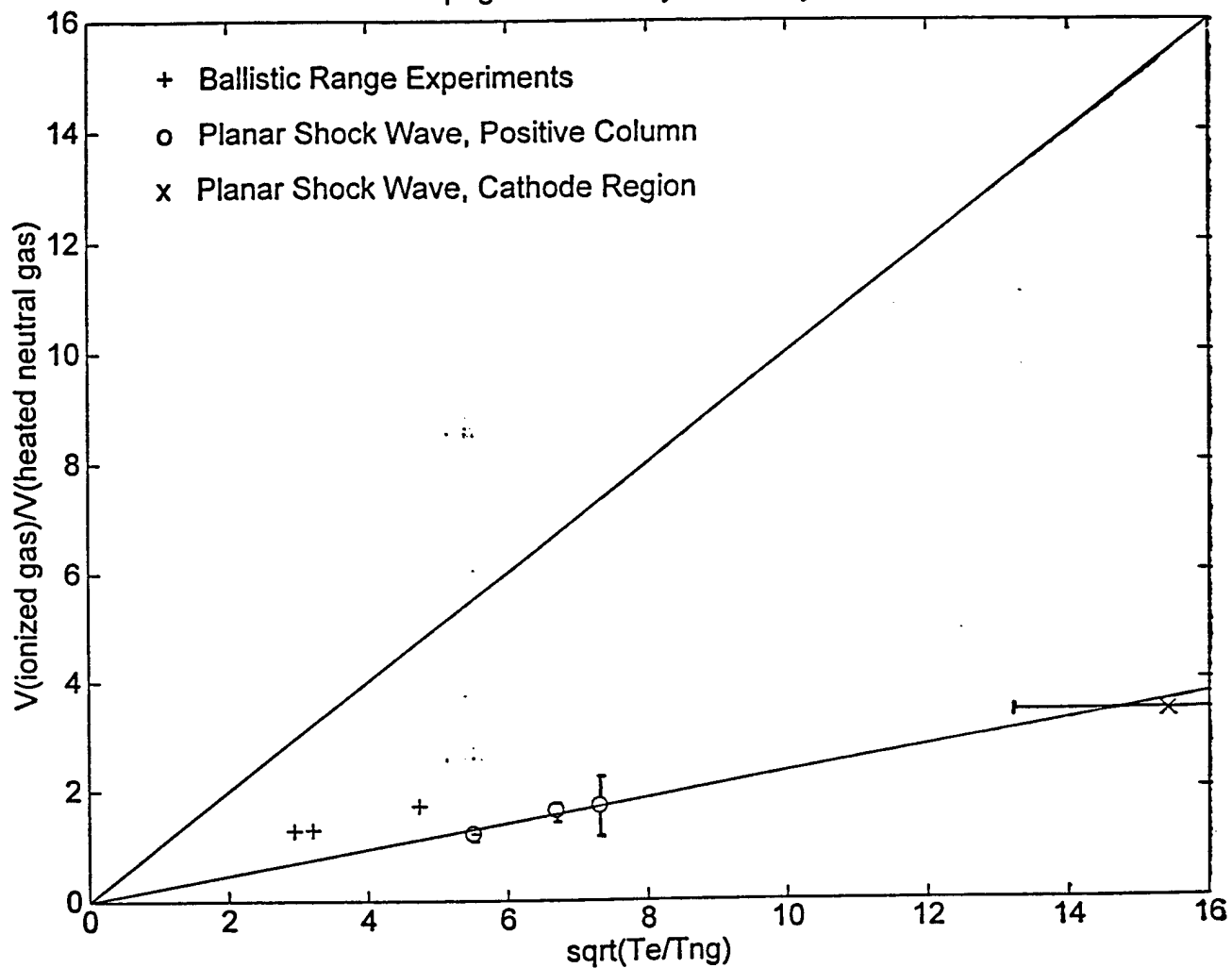
B.



Shock Front Velocity in Cylindrical Glow Discharge [Phys. Lett., A230, 218-222 (1997)]



Shock Propagation Velocity in Weakly Ionized Gas



Metastable States

• Oxygen	$a^1\Delta_g$	(0.97 - 5) eV
• Nitrogen	$A^3\Sigma_u^+$	(6.17 - 8.83) eV
• Argon	$1s_{3,5}$	11.55 eV & 11.72 eV
	$2p$	(12.91 - 13.48) eV

Relevant Collision Processes

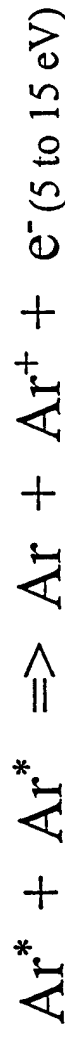
- Electron impact ionization

Dominant ionization mechanism at high pressures.



- Energy pooling reactions

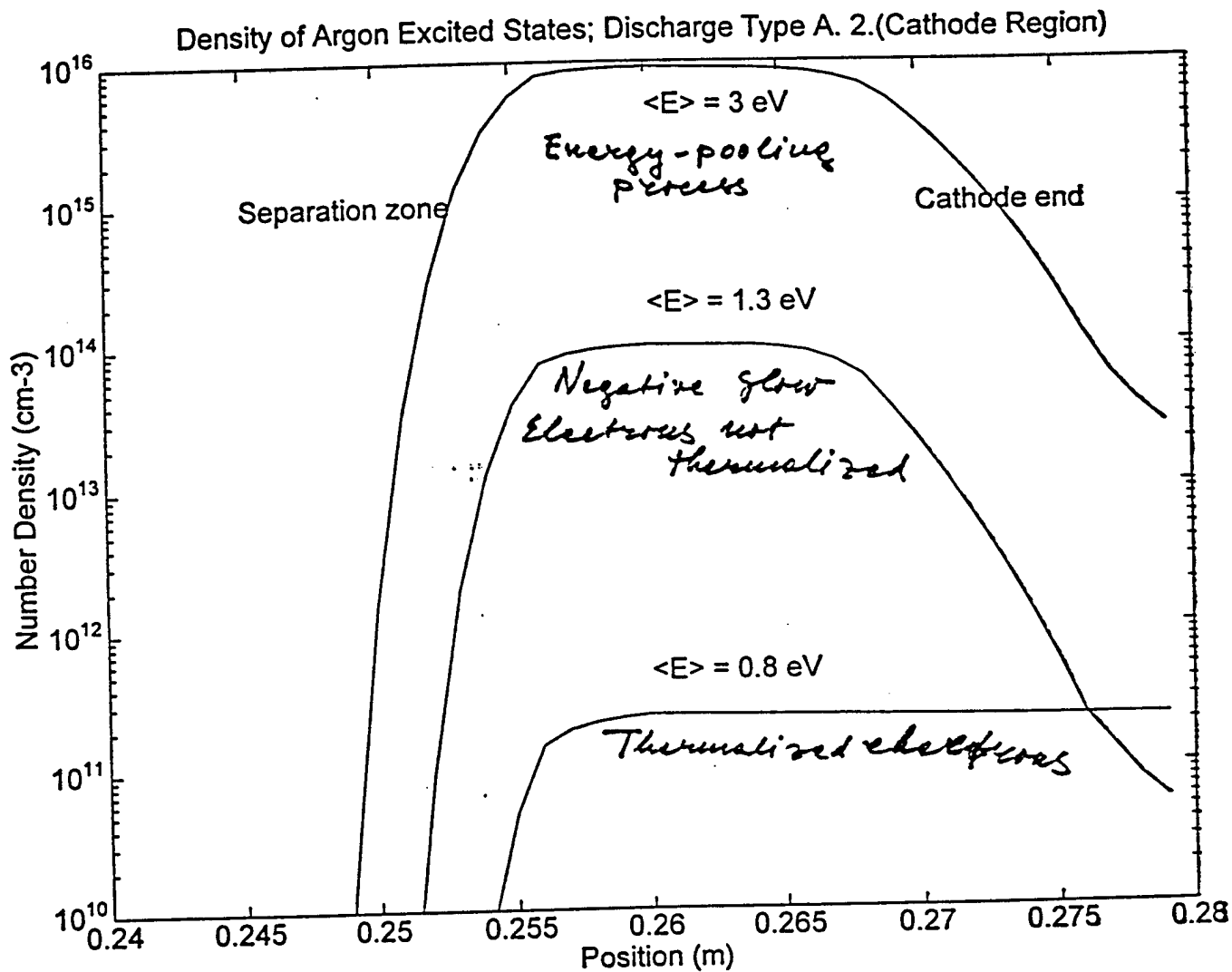
Dominant ionization mechanism at medium pressures.

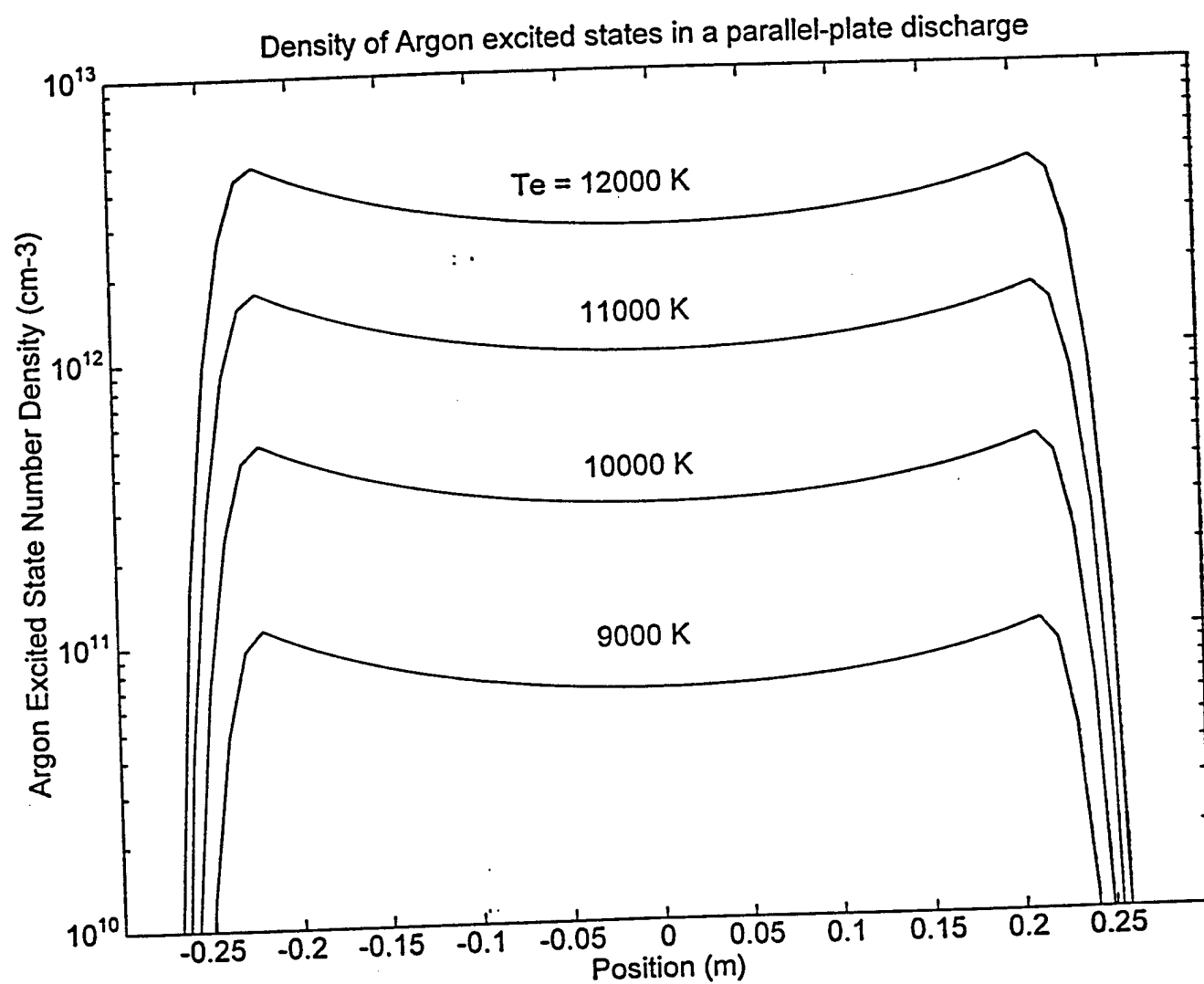


(Density breakdown, “oven effect” of Rydberg states).

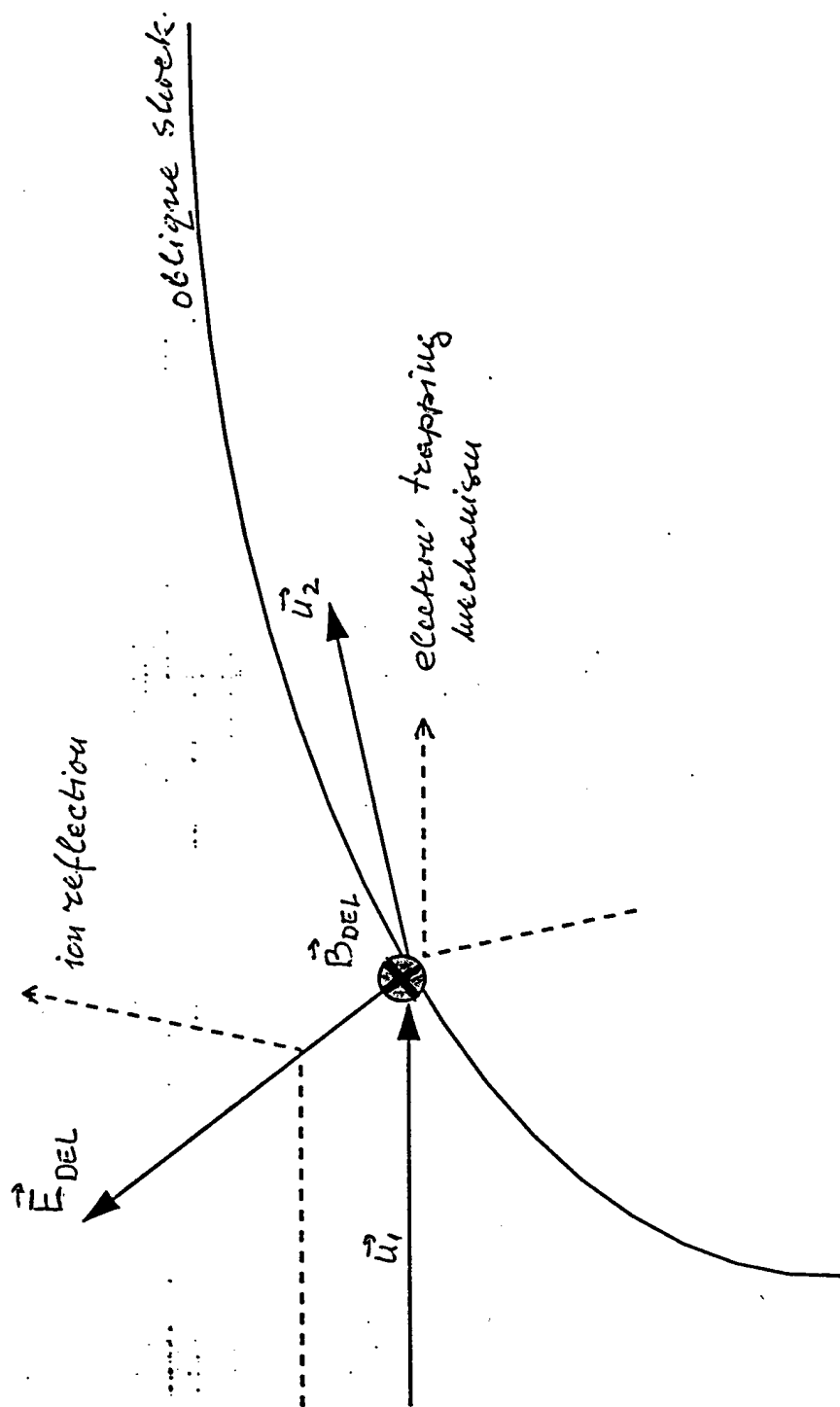
- Charge Transfer



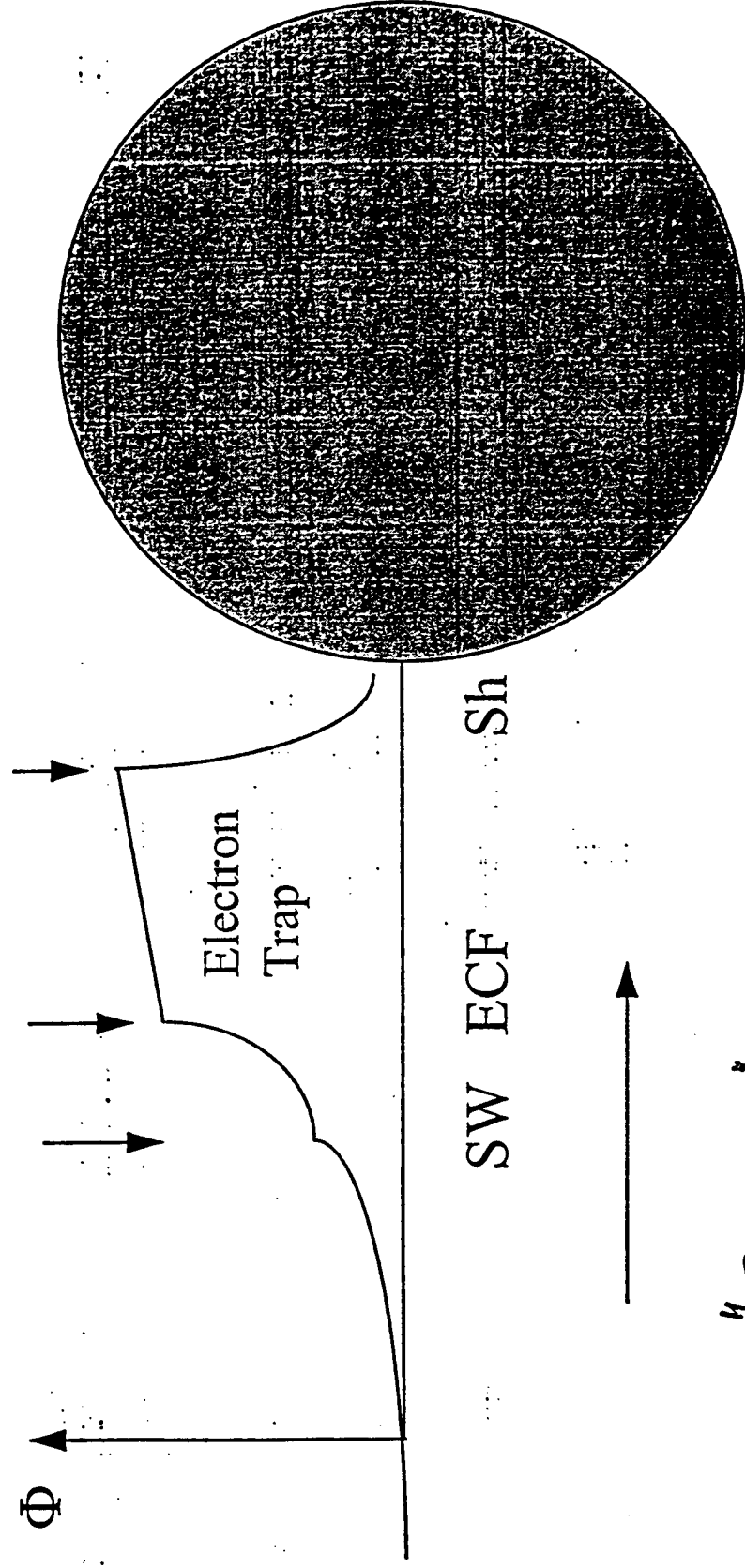




EM Field at DEL



Electric Potential Distribution on the Centerline



"Storage" mechanism
(most energy stored in "electron trap" region)

Shock Structure

Relaxation (ECF)

"Residual"

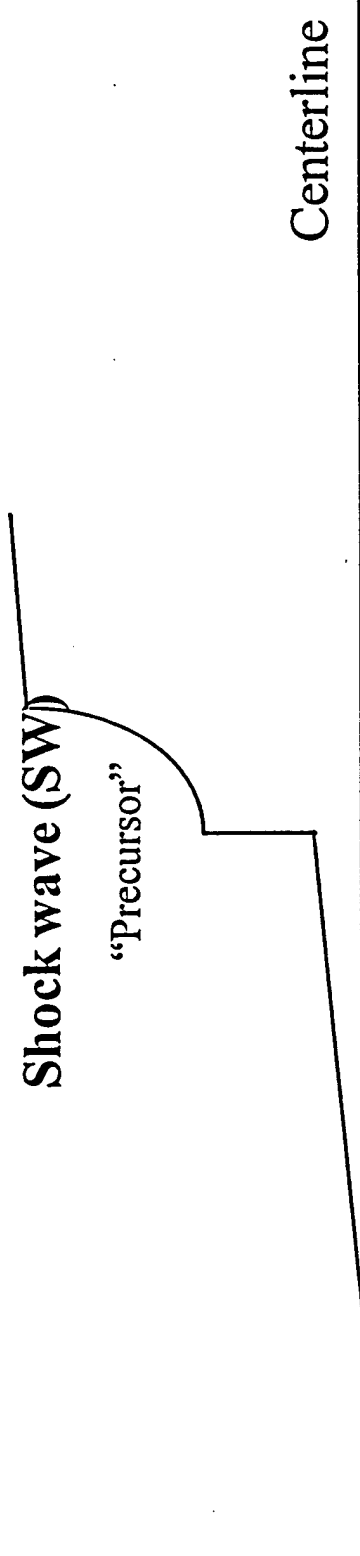
Shock wave (SW)

"Precursor"

Centerline

Precursor

"Leader"



Effects which Follow Initial Perturbation

— Ion dynamics

- Shock wave generates a Double Electric Layer (DEL).
- DEL generates an ion acoustic wave.
- Local increase of ion density traveling with the wave.
- Slow ions reflected from DEL.

— Electron dynamics

- Moving DEL induces transversal **B** field.
- **B** field confines slow electrons.
- Fast electrons escape DEL.
- Most electrons trapped in relaxation zone
- Electrons heated by inverse bremsstrahlung.

Precursor

- Fast Ions reflected and accelerated on DEL
 - able to excite and ionize atoms and molecules
- Fraction of hot electrons heated by:
 - *inverse bremsstrahlung* (observed difference in population of resonant and metastable states)
 - *energy pooling reactions*
- Mechanisms:
 - A. Ion-acoustic wave
 - B. Ionization wave generated by heavy particles (fast ions and neutrals)?
 - C. Onset of turbulence by angular momentum transfer in energy pooling reactions?

**ON-BOARD GENERATION OF A "PRECURSOR" MICROWAVE
PLASMA AT MACH 6: EXPERIMENT DESIGN**

R. J. EXTON

**NASA AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER**

MACH 6 PLASMA/Drag REDUCTION TEAM

MEMBER

R. J. EXTON

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M. DIFULVIO

W. E. LIPFORD

J. FUGITT*

M. C. BAILEY

W. C. KELLIHER

I. A. CARLBERG

G. C. HERRING

B. SHIRINZADEH

P. D. BABB

A. H. AUSLENDER

D. B. RHODES

S. JONES

PRIMARY RESPONSIBILITY

EXPERIMENT DEFINITION

VISUALIZATION/LASERS

MODELS/FACILITY

FACILITY

OPTICAL SUPPORT

MICROWAVE (EXPERIMENT)

MICROWAVE (THEORY)

NUCLEAR SOURCES

NUCLEAR SOURCES

ELECTRON DENSITY

NEUTRAL DENSITY

SAFETY

CPD

SCHLIEREN

SCHLIEREN

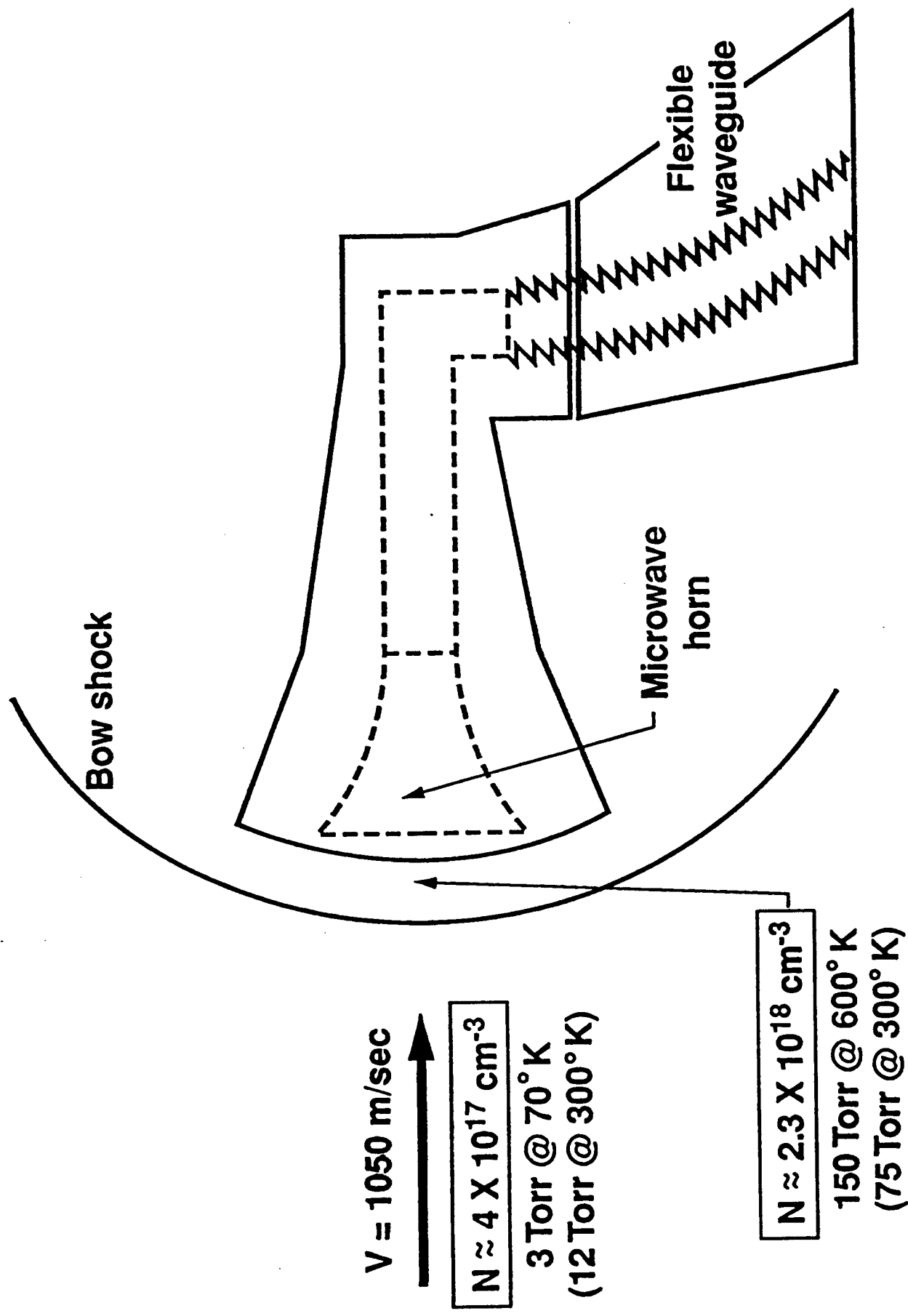
OBJECTIVES:

1. Experimentally demonstrate a concept for on-board generation of a microwave plasma;
2. Develop plasma diagnostic techniques for low density (cold) plasmas;
3. Clarify the physics underlying the phenomenon in conjunction with a parallel CFD effort.

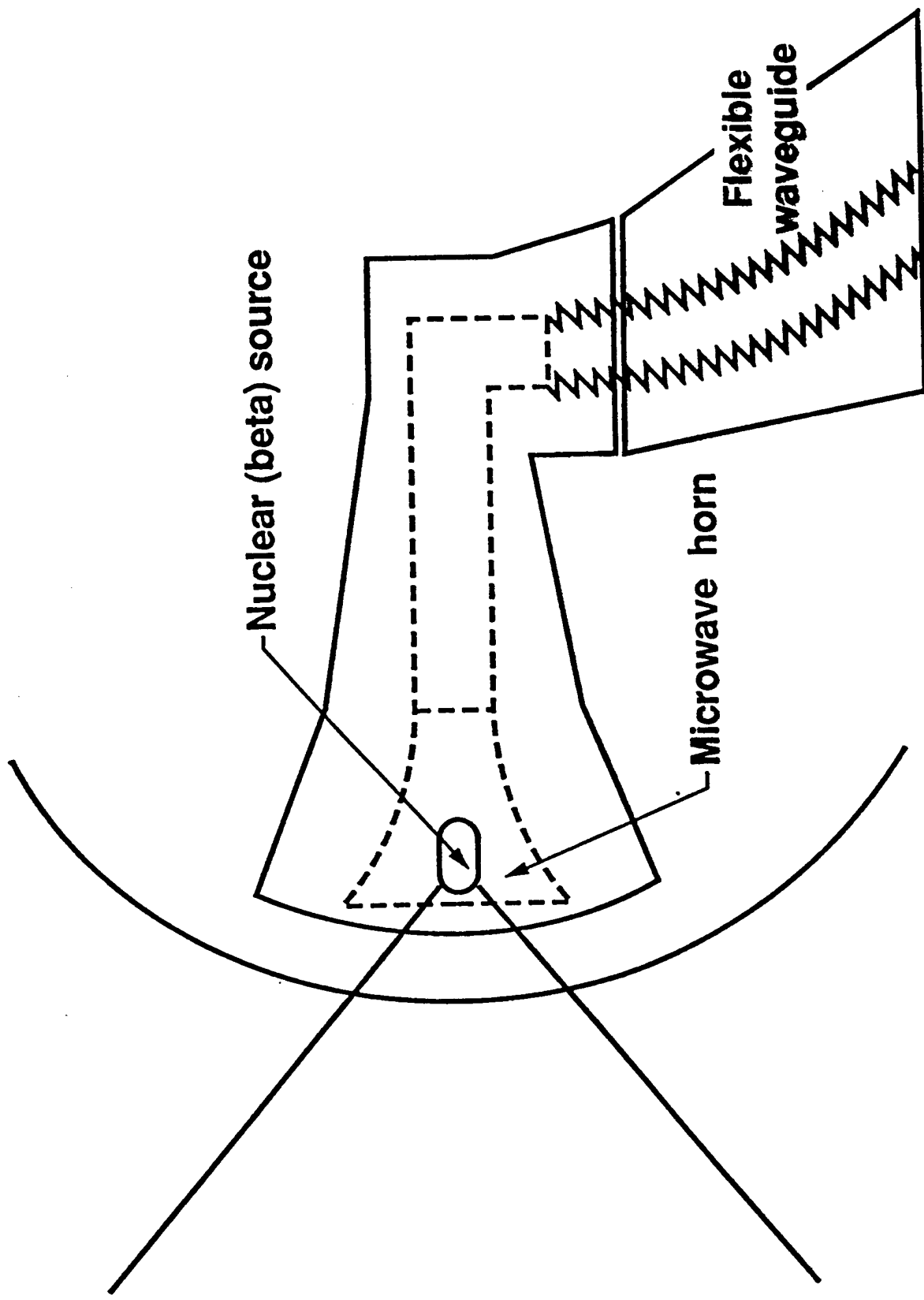
APPROACH

- Design model/microwave horn for Mach 6 facility conditions
- Measure the forces on the model (plasma on/off)
- Characterize the plasma flow field (shock standoff and shape, electron density and temperature, neutral density profile)
- Investigate both cw and pulsed microwave power amplifiers as plasma generators

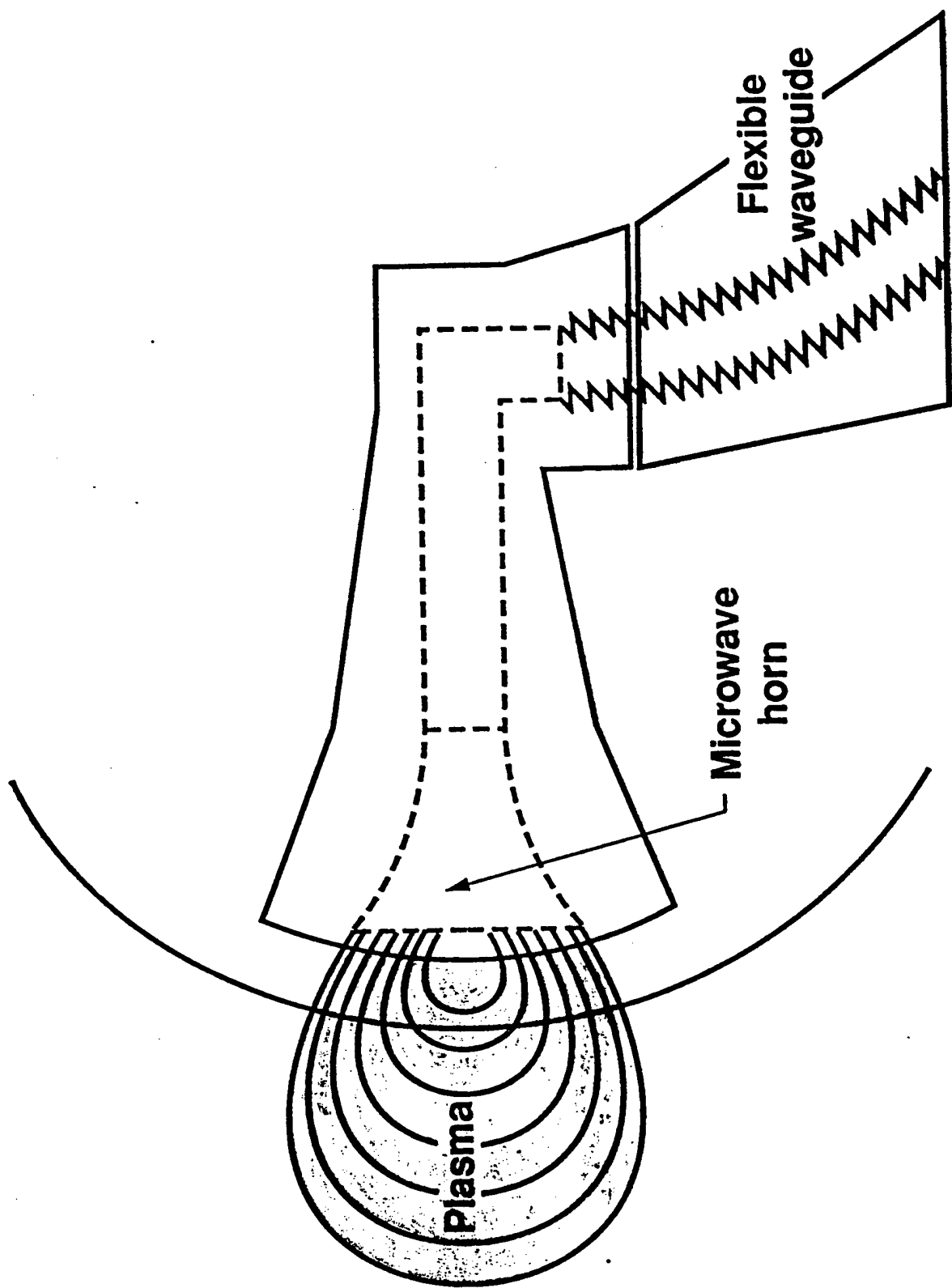
"Precursor" Microwave Plasma at Mach 6



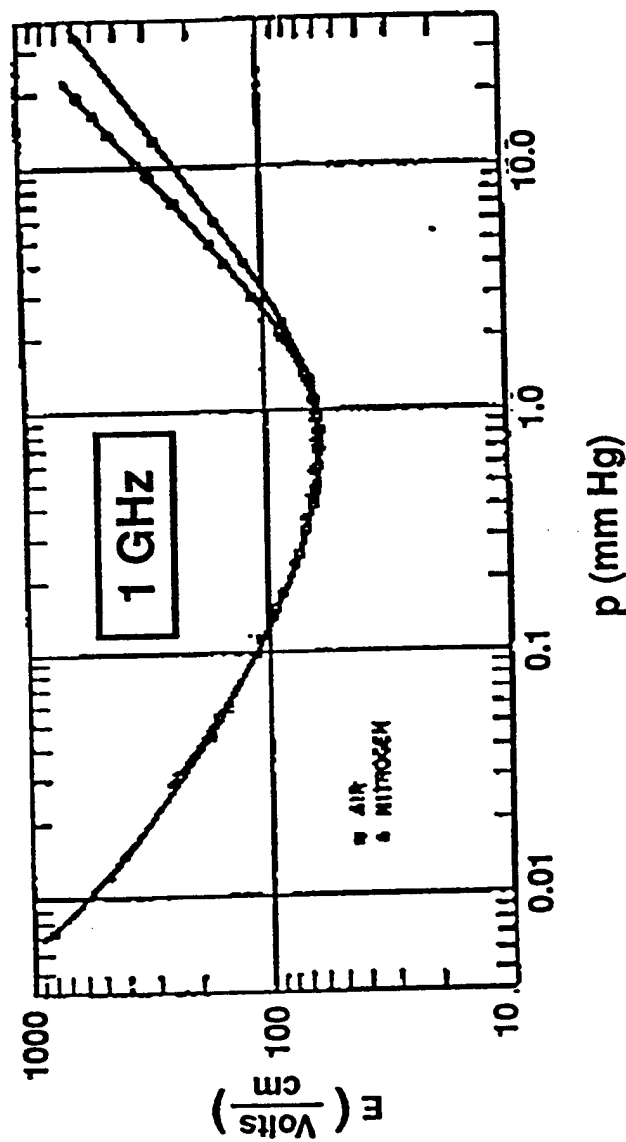
"Precursor" Microwave Plasma at Mach 6



"Precursor" Microwave Plasma at Mach 6

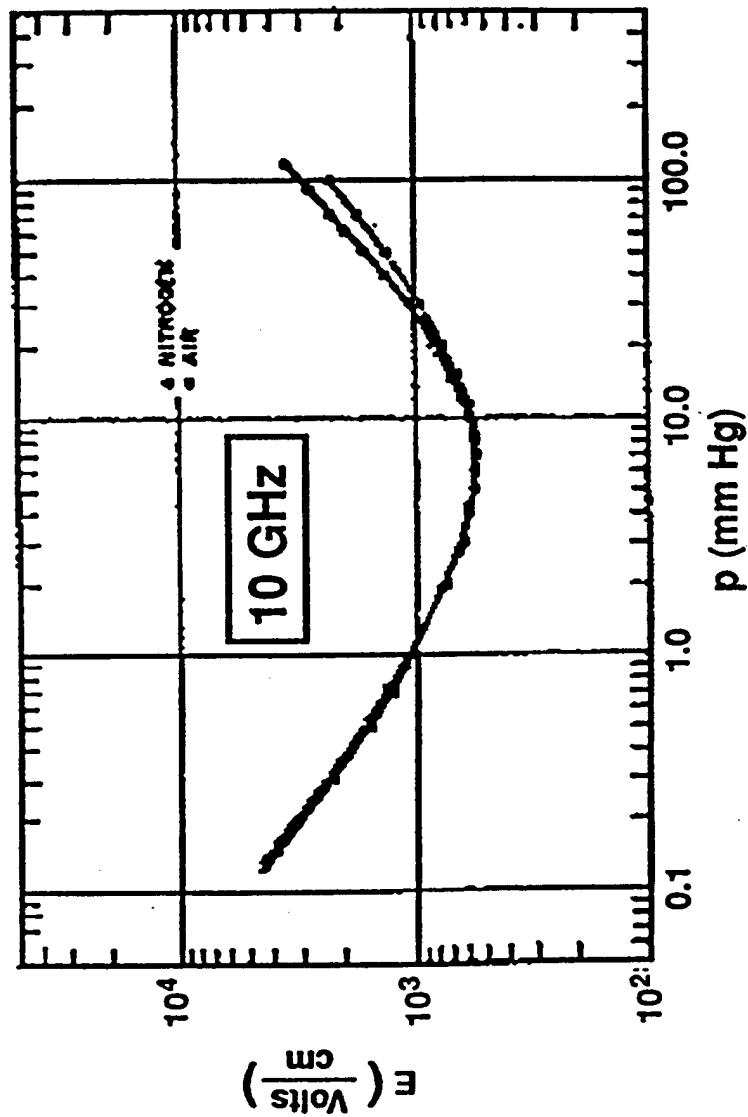


Microwave Breakdown in Air, O, and N



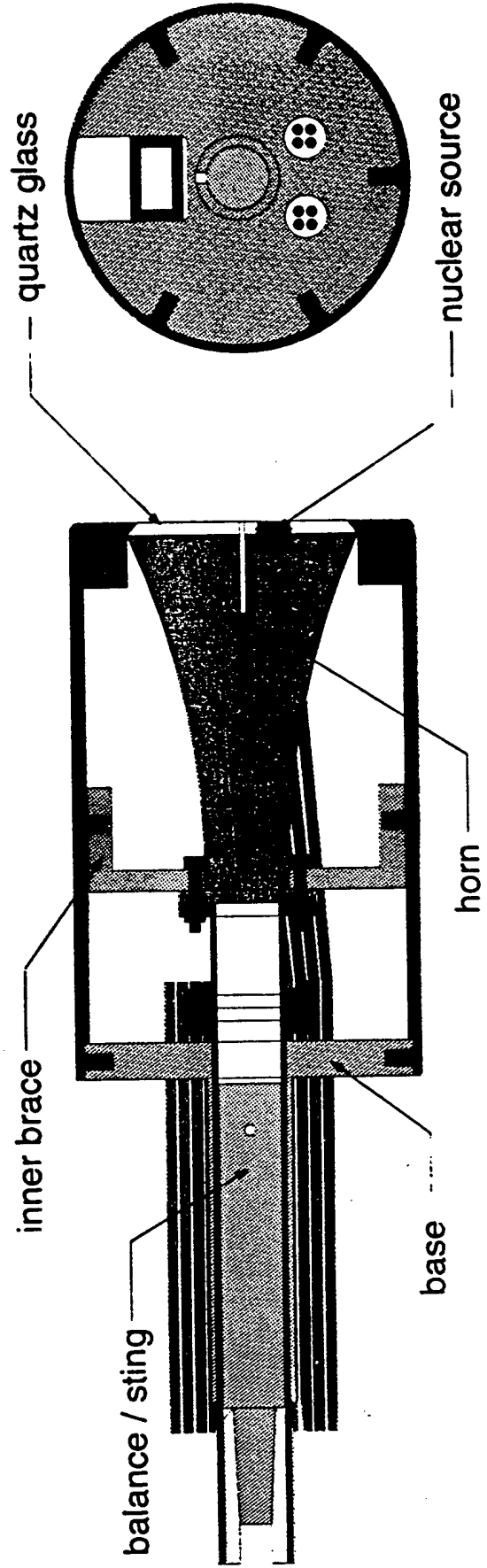
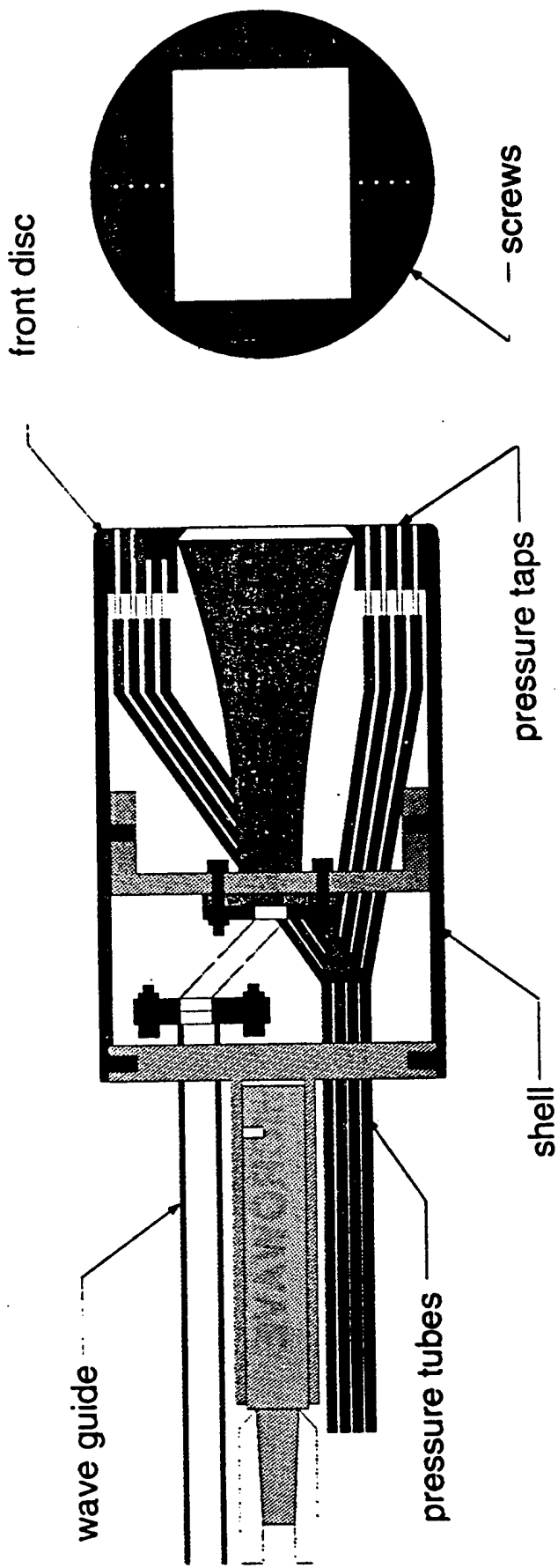
Cw breakdown fields for air and nitrogen at a frequency of 994 Mc/sec.
 (Characteristic diffusion length $A = 2.65 \text{ cm}$)
 A. D. MacDonald et. al. Phys. Rev. 130, 1841 (1963)

Microwave Breakdown in Air, O, and N



Cw breakdown fields for air and nitrogen at a frequency of 9.4 kMc/sec.
(Characteristic diffusion length $A = 0.22$ cm)
A. D. MacDonald et. al. Phys. Rev. 130, 1841 (1963)

PLASMA DRAG REDUCTION MODEL



DIAGNOSTICS

INITIAL ENTRY

- 0 PULSED, DIGITAL SCHLIEREN
- 0 GATED, CCD CAMERA
- 0 OPTICAL MULTICHANNEL ANALYZER
(200-900 NM)

FUTURE ENTRIES

- 0 EXCIMER LASER (NEUTRAL PROFILE)
- 0 LASER/MICROWAVE INTERFEROMETRY
(ELECTRON DENSITY)

SCHEDULE/MICROWAVE POWER

SCHEDULE-MACH 6

POWER AMPLIFIERS (AVAILABILITY)

INITIAL ENTRY ~AUG 97

*	<u>CW</u>	0	200 W, 8-18 GHz	(AVAILABLE)
*				
*		0	500 W, 8-18 GHz	(POSSIBLE LOANER)
*				
*		0	2 kw @ 14 GHz	(COMMERCIAL)
*				
*		0	10 kw @ 18 GHz	(?????)
*				

2ND ENTRY--FY98

*	<u>PULSED</u>	0	26 kw PEAK, X-BAND (8.2-12.4 GHz) 5% DUTY 1.3 kw AVG.	(POSSIBLE LOANER)
*				
*		0	100 kw PEAK, X-BAND (8.2-12.4 GHz)	(POSSIBLE LOANER)
*				
*		0	100 kw PEAK, KU-BAND (12.4-18.0 GHz) 3 MICROSEC PULSE 100 Hz	(POSSIBLE LOANER)
*				
*				

CONCERNS

- SUFFICIENT FIELD STRENGTH FOR BREAKDOWN
(~700 V/CM @ 10-15 TORR)
- PLASMA EXTENT SUFFICIENT TO ATTAIN "PRECURSOR"

STATUS

- ELECTRON DENSITY AND TEMPERATURE ADEQUATE TO
BRING ABOUT SHOCK MODIFICATION

SOLUTION

MORE POWER

Program Overview

Shock Wave Dynamics in Weakly Ionized Plasmas

at

Laboratory for Modern Fluid Physics, Florida A&M University (FAMU), Tallahassee, FL

Prof. J. A. Johnson III, Distinguished Prof. of Science and Engineering

Dr. Richard Appartaim, Research Associate in Physics

Mr. Kester Thompson, Graduate Student, Mechanical Engineering

Overall FAMU Purpose

To determine the roles which turbulence and/or nonequilibrium effects in weakly ionized gases play in shock wave transport dynamics through:

- (a) comprehensive optical diagnostics of the interactions of shock waves with turbulence and/or nonequilibrium plasmas in the low supersonic and hypersonic regimes;
- (b) rigorous analyses of the associated physics, including quantummechanical as well as classical phenomena;
- (c) explorations of potential modalities for the implementation of plasma drag reduction of operational aircraft.

Recent FAMU Achievements

- > Evidence of shock wave strength reduction from a turbulence manipulated nonequilibrium flow in a pressure ruptured shock tube;
- > Preliminary evidence of shock wave acceleration in our new Supersonic Shocked Plasma Facility where a Mach 2 shock wave moves from a plasma free region into one with a weak plasma;
- > Preliminary evidence from our Hypersonic Arc Driven Shock Tube of highly localized energy transfer from small scale turbulent nonequilibrium fluctuations into large scale flow of the sort which can weaken the strength of a resident shock wave.
- > Preliminary experimentally testable explanations of the influence of turbulence and/or nonequilibrium effects on standard macroscopic transport quantities

Specific Immediate FAMU Plans

- > Modifications of our current Supersonic Shocked Plasma Facility to afford a wider variety of manipulations in the shock wave-plasma interaction, including the introduction of seed molecules and microwave probes;
- > System-specific modelling of the plasma and atomic processes so as to determine the underlying physics along with a full range of test modalities, including those relevant to ballistic ranges, flight, and other configurations different from our own;
- > The implementation of a new Turbulent Stark Velocimetry as a program of development of relevant portable diagnostics suitable for possible near term introduction on operational airframe platforms.

AERODYNAMIC APPLICATIONS OF WEAKLY IONIZED PLASMAS

R. Miles, S. Macheret, S.H. Lam, P. Efthimion, L. Martinelli
Princeton University

- Drag Reduction
- Plasma Ramparts
- Flow Control
 - By Localized Energy Addition
 - By $\mathbf{J} \times \mathbf{B}$ forces
- Control and Initiation of Chemical Processes
- Power Extraction
 - MHD in an engine inlet (AJAX)
 - MHD in ionized flow
- Hypersonic Wind Tunnel Drivers
 - By Energy Addition through microwaves
 - By MHD acceleration
- Suppression of shock strength and sonic boom

SUSTAINING A PLASMA IN HIGH SPEED FLOW

- Important for Drag reduction, Plasma Ramparts, Flow Control, Shock Suppression, MHD, and Combustion Initiation and Control
- Discharge may be blown out
- Thermal (equilibrium) plasma will need to be reinitiated - a thermal plasma cannot propagate at supersonic speed
- Nonequilibrium plasma will require high electric field and high power
- A filamentary plasma may serve the purpose and will require less power (a small portion of the volume is ionized)
- Filaments may be guided by laser or electron beams
- A high power microwave may be the preferred source.

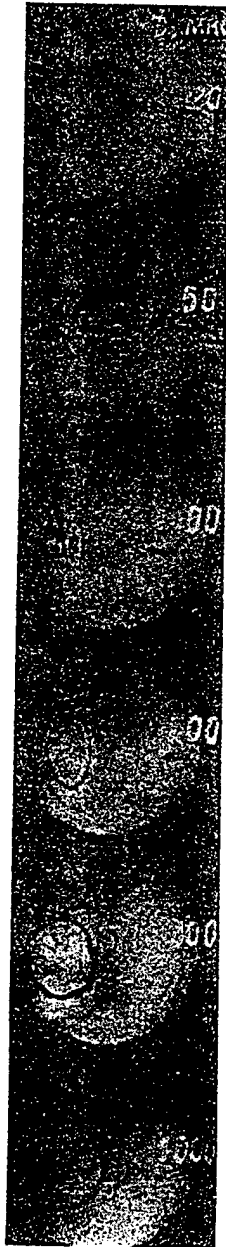
SUSTAINING MICROWAVE DRIVEN PLASMAS IN ATMOSPHERIC PRESSURE AIR

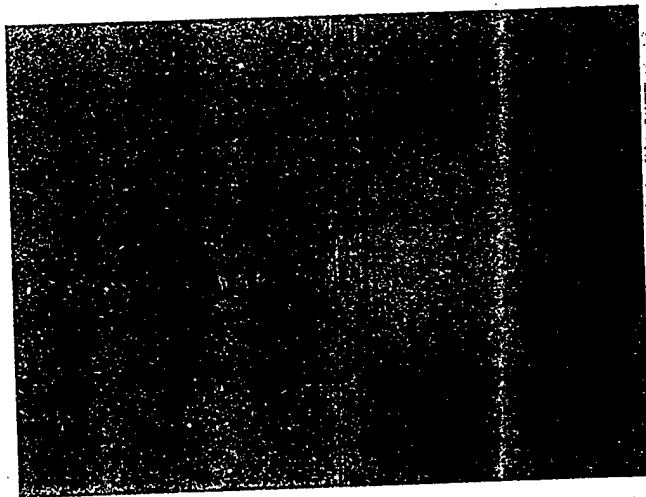
- Thermal Regime

- Requires $T_{\min} > 4000\text{K}$
- Needs relatively low microwave power (kilowatts/cm^2)
the power offsets the thermal losses
- Long lifetime (cooling time)

- Nonequilibrium Regime

- Requires high power microwaves to overcome the electron
recombination and attachment rates
- Diffuse plasma (low pressure)
 - Low temperature neutral species
- Filamentary discharge (high pressure)
 - High temperature localized streamers

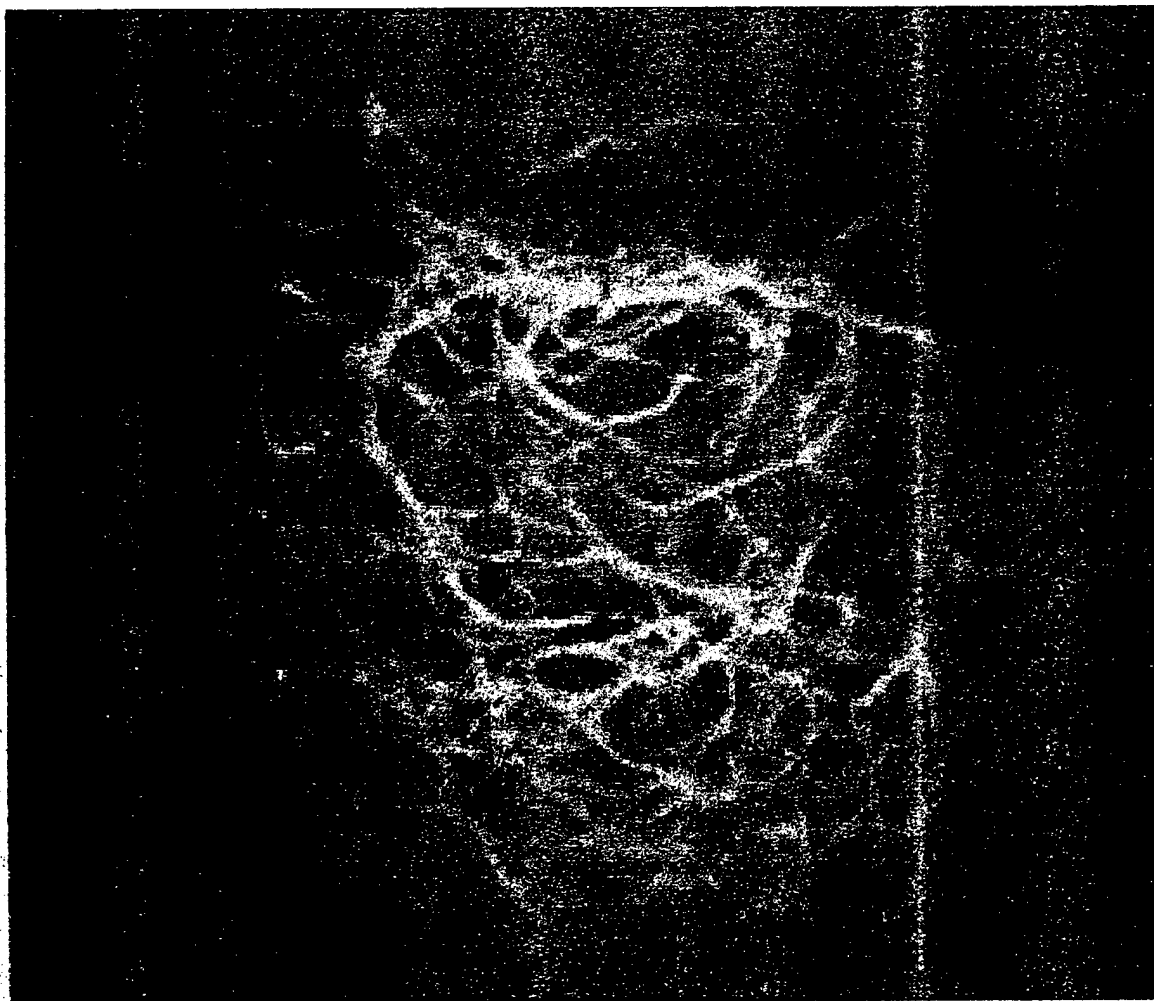




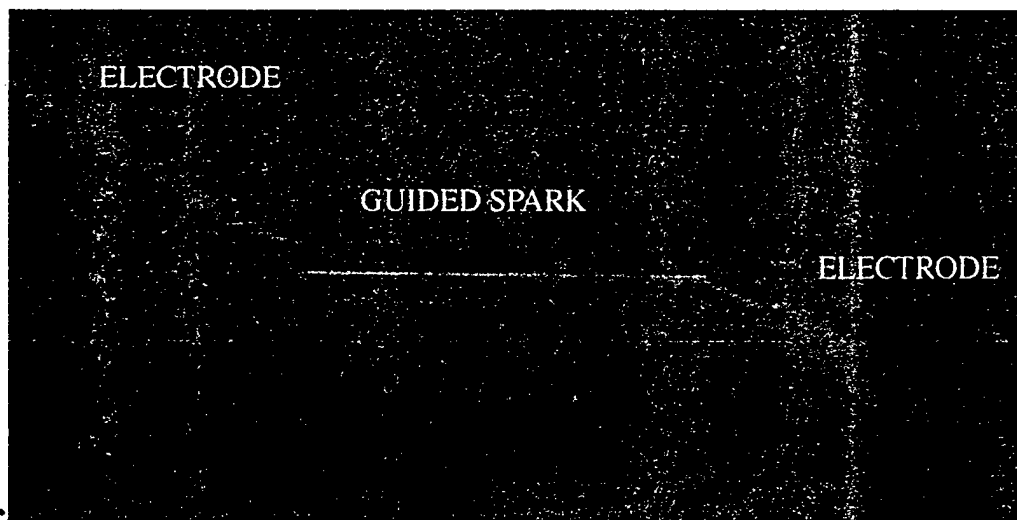
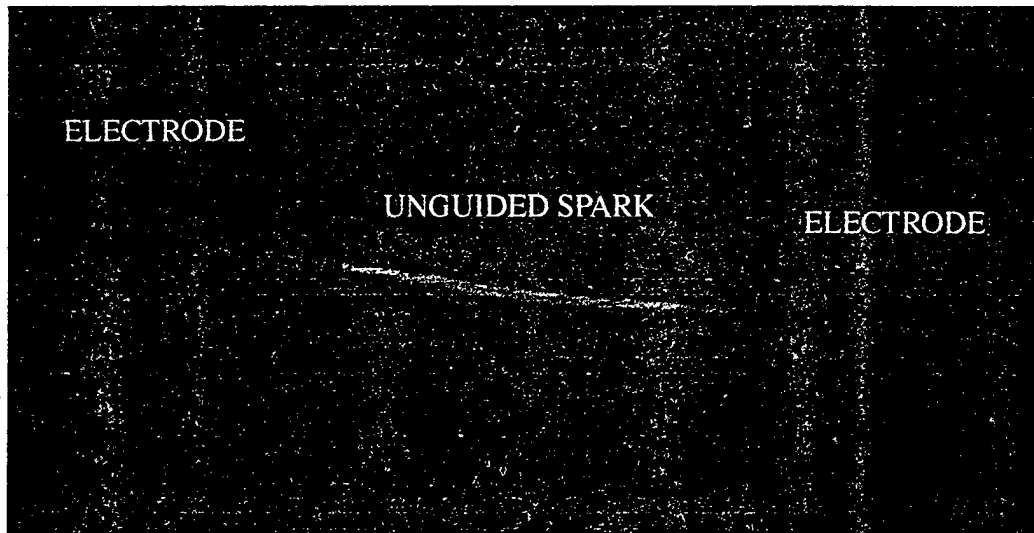
FILAMENTATION OF ATMOSPHERIC
MICROWAVE DRIVEN PLASMA

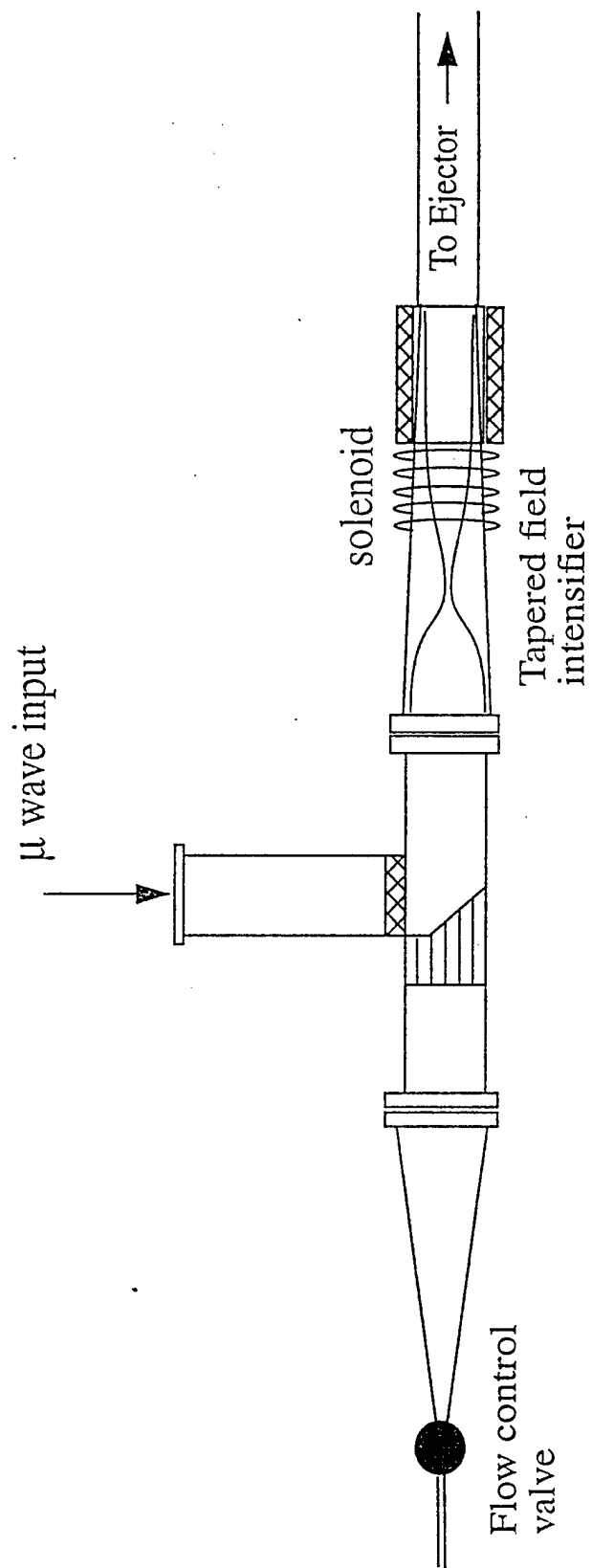
Grachev, Esakov, Mishin and Khodataev

Moscow RadioTechnical Institute



LASER GUIDED ARC FORMATION



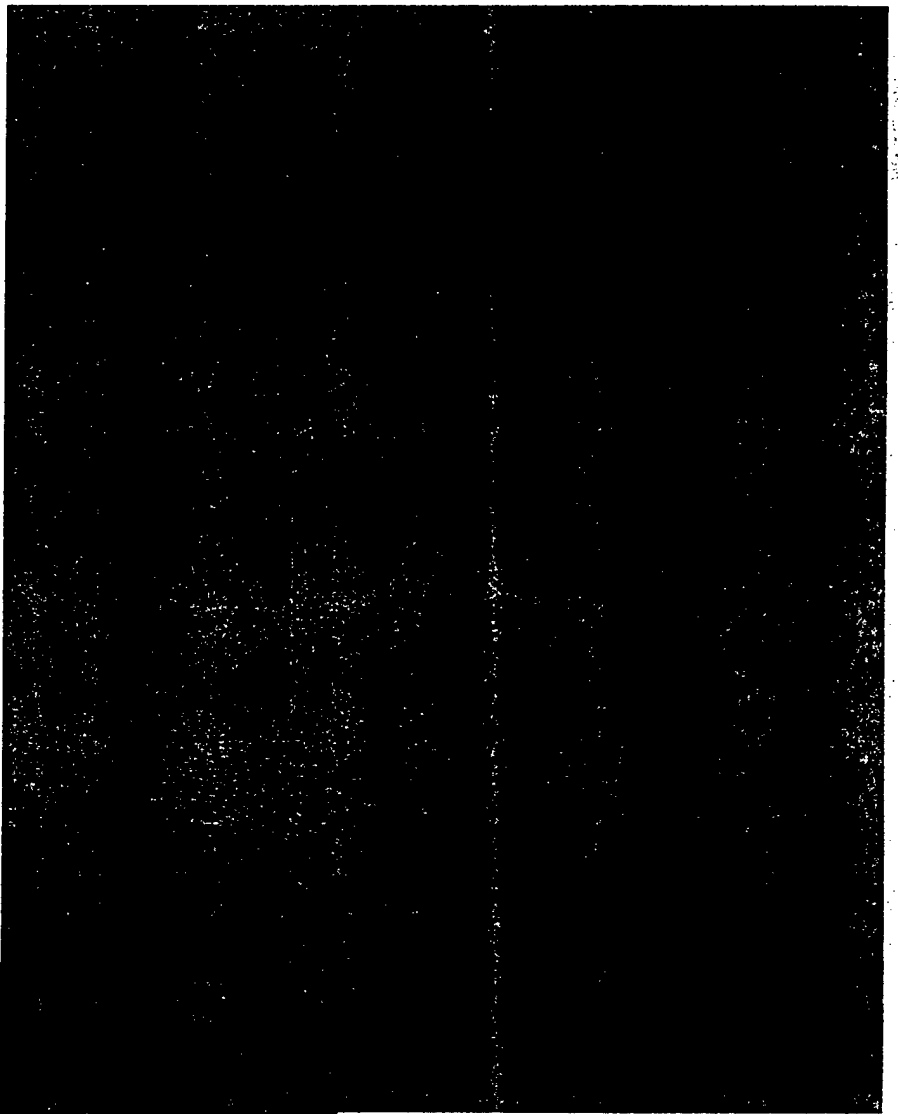


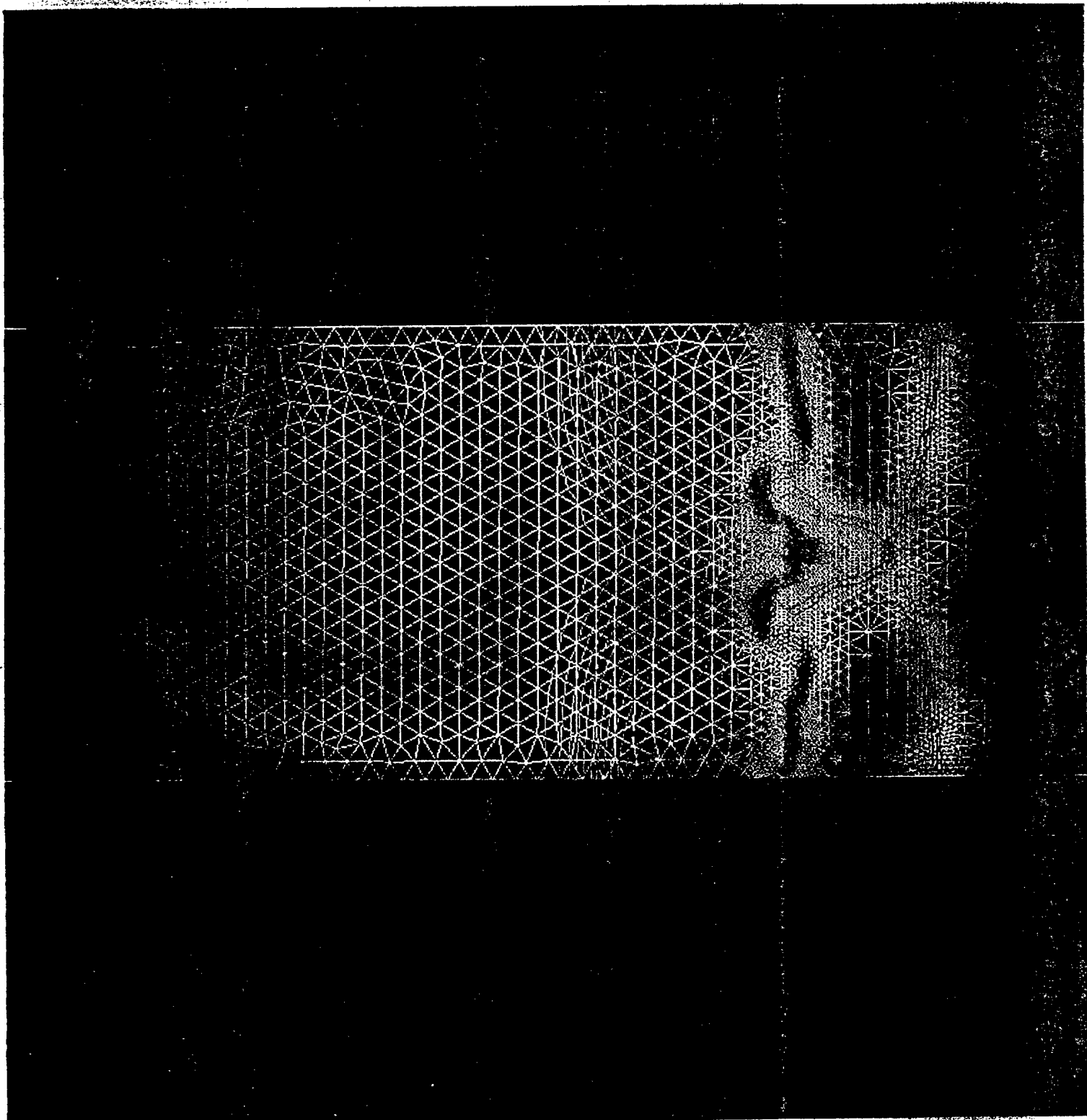
DRAG REDUCTION

Experimental Observations

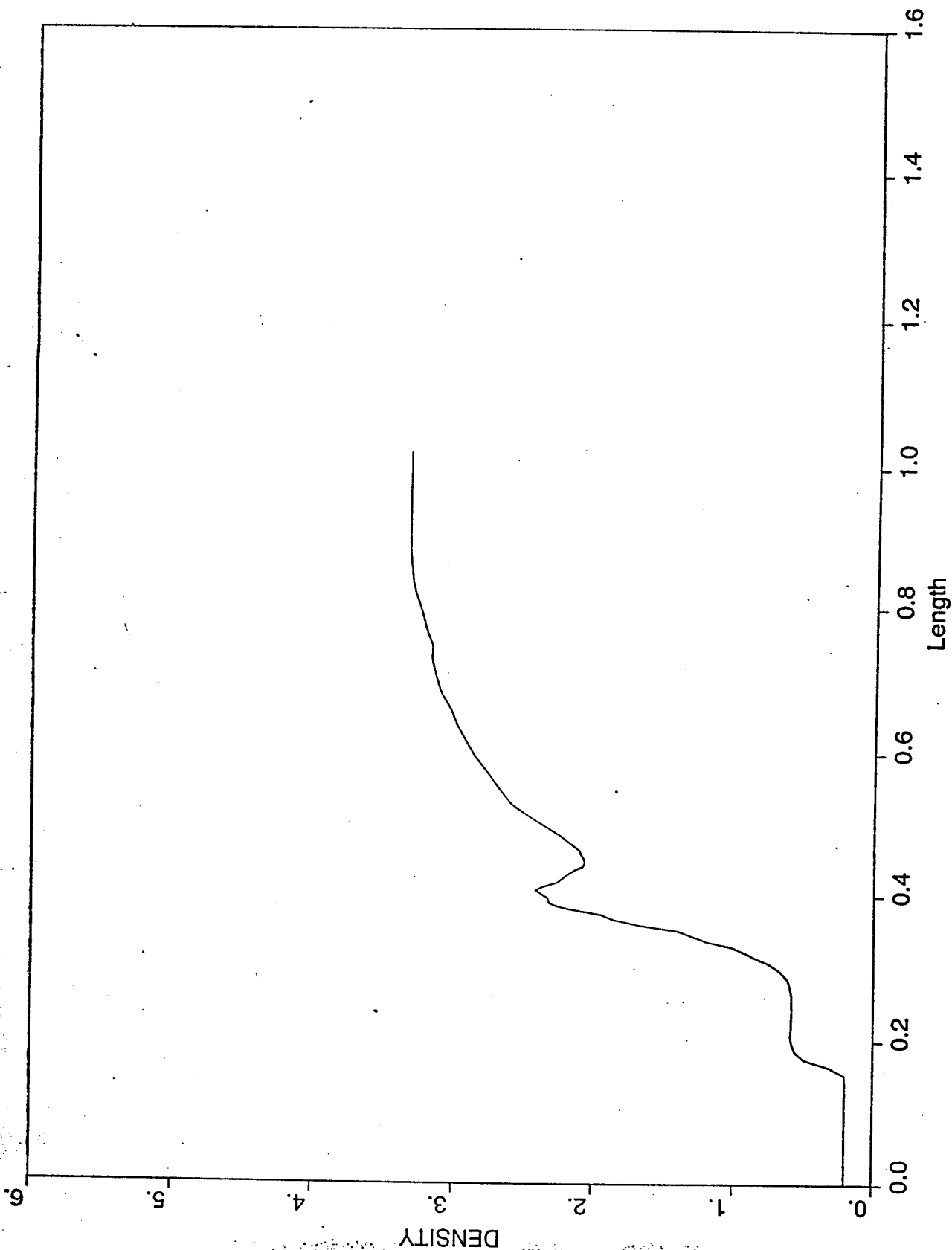
- Shocks Accelerate Upon Entry Into Plasmas From Neutral Gas
- Dramatic Changes In Structure:
 - Shock Front Broadens
 - Amplitude Decreases
 - Shock Typically Splits Into Two or Three
- Effect Persists for Quite a Long Time (up to 1 - 10 msec)
- Observations Were Made In Various Discharges (Longitudinal And Transverse), In Various Gases (Air, Argon, Hydrogen, Helium, Etc.) Using Various Diagnostics.
- Ballistic Range Experiments Seem to Imply a Change in the Effective Speed of Sound, and Show Decrease in Supersonic Drag.

The image is a dark, grainy, black and white scan, likely of a document page. It is heavily degraded with significant noise, including numerous white specks and artifacts. A vertical line of lighter, textured material runs down the right side of the image, possibly indicating a page fold or a scanning artifact. The overall appearance is that of a very poor quality reproduction of a document.



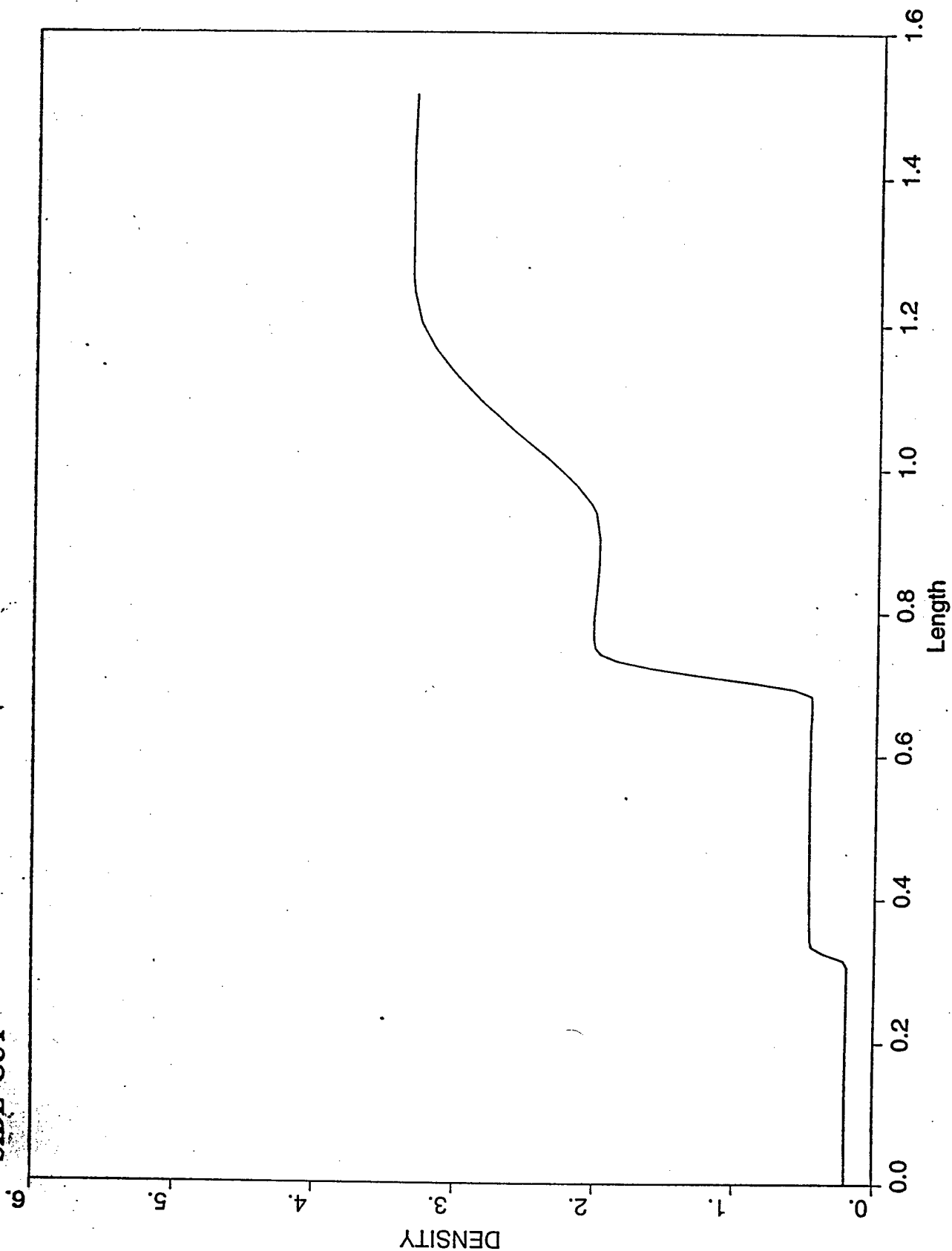


DENSITY PROFILE ACROSS THE SHOCK IN "THERMAL DIAPHRAGM" CASE
(CURVED BOUNDARY BETWEEN HOT AND COLD REGIONS)
CUT ALONG THE CENTER LINE.

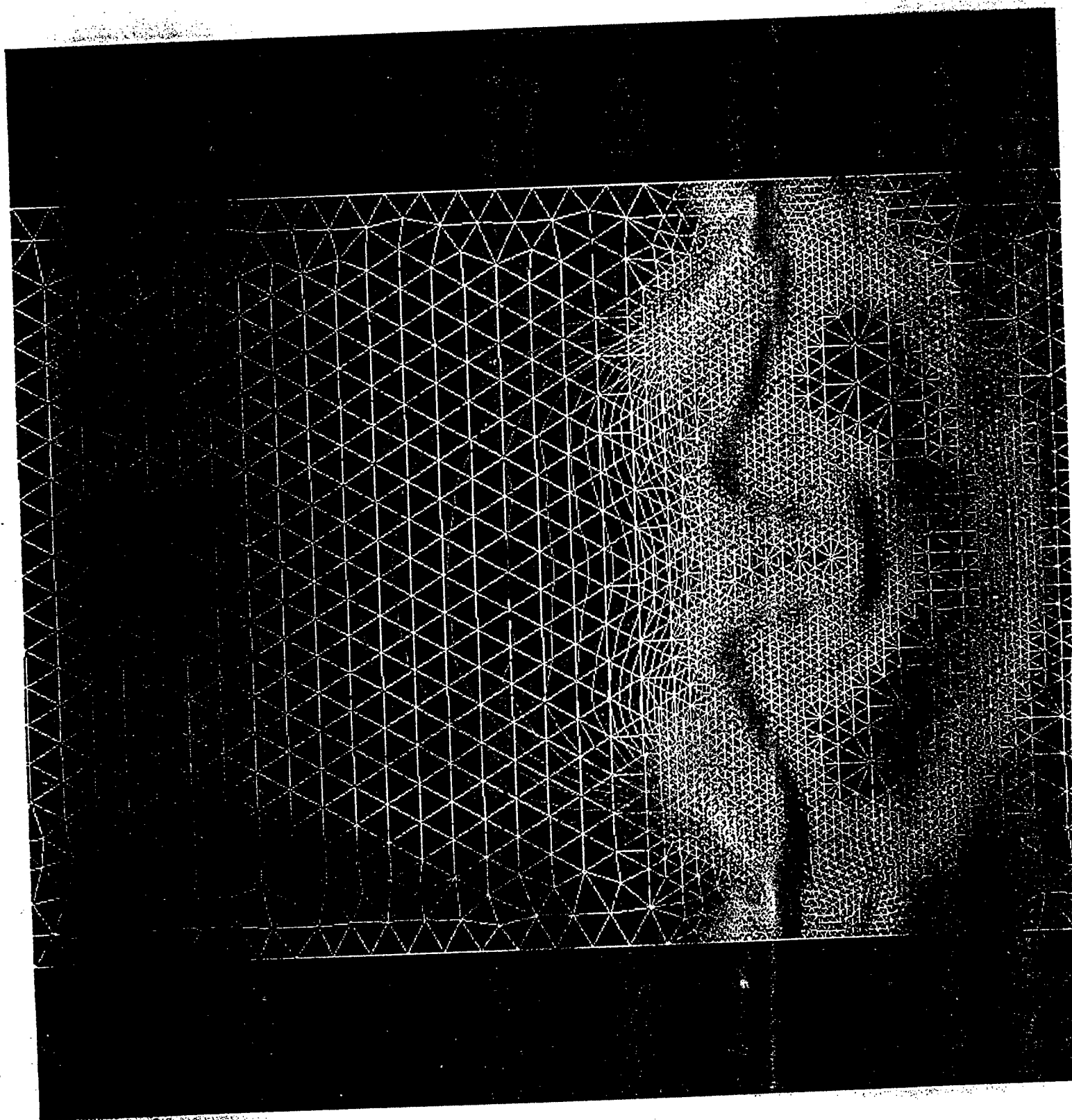


Planar Cut @ (0.83, -0.24, 0.25)(0.83, 0.74, 0.25)(1.82, -0.24, 0.25)

DENSITY PROFILE ACROSS THE SHOCK IN "THERMAL DIAPHRAGM" CASE (CURVED BOUNDARY BETWEEN HOT AND COLD REGIONS) SIDE CUT



Planar Cut @ (1.01, -0.28, 0.25)(1.01, 1.26, 0.25)(2.55, -0.28, 0.25)



EXPERIMENTAL CONCERNS

- Temperature

- In all the experiments, the temperature of the neutral gas has not been directly measured.

- Temperature Profile

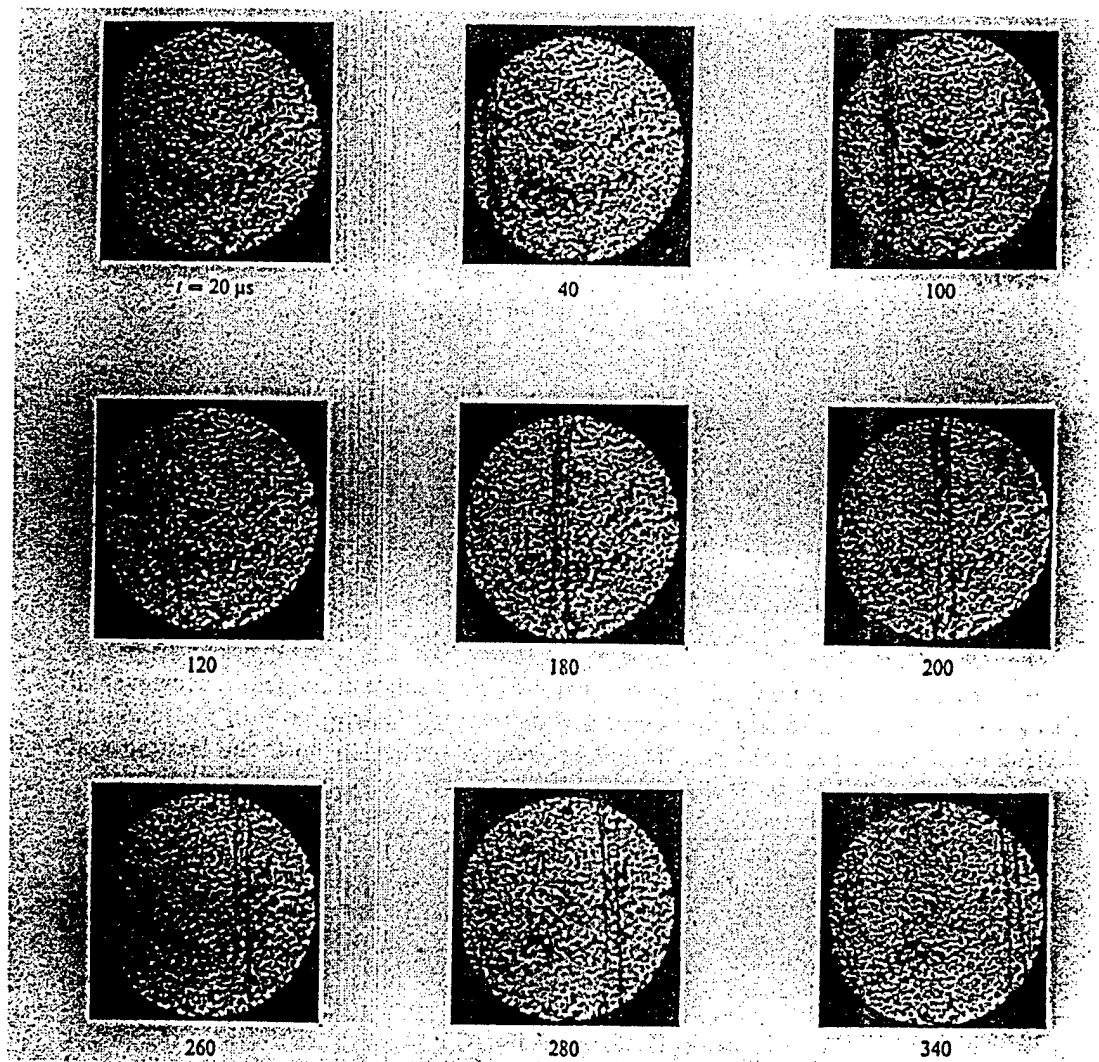
- A transverse temperature profile or a curved thermal boundary will lead to complex shock structure. This may occur as the shock passes through the hot cathode or anode fall regions of the discharge. (Well away from the centerline of the experiment)
- Models indicate the apparent shock splitting and the density rise echo experimental observations

- Nonuniform Temperature Field

- Shock splitting has been seen in turbulent mixtures of gases. If the plasma has hot and cold regions, a similar shock break-up may occur.

M = 1.03 SHOCK PROPAGATION THROUGH
HE + R 12 TURBULENT MIXTURE

Hesselink and Sturtevant



CONCLUSIONS ON DRAG REDUCTION

- All the experimental phenomena we examined are consistent with thermal gradient effects
- Ballistic range data needs to be studied in more detail
- Accurate temperature and density measurements need to be made
- There may be some effects of thermal gradients, unsteady phenomena, vorticity, and random or flickering heat addition.

PRINCETON PROGRAM

- Development of new diagnostics for temperature and density imaging

- New World Vistas
 - Sustaining microwave driven plasmas in a Mach 3 flow
 - Plasma effects on the bow shock in a Mach 3 flow.
 - Study of basic mechanisms of acoustic wave interactions and shock dynamics in stationary plasmas

- Plasma Ramparts
 - Experimental studies of the control of plasma filamentation
 - Kinetic model development for pulsed ionized air plasmas
 - Modeling nonequilibrium molecular processes
 - High power microwave driven discharge dynamics
 - Stabilizing and extending microwave driven plasmas with magnetic fields

- Mariah II (Radiatively Driven Wind Tunnel augmented by MHD)
 - Sustaining conductivity in atmospheric pressure air with electron beams
 - Acceleration and deceleration of supersonic flows in MHD channels
 - Energy coupling into high pressure air
 - MHD acceleration with filamentary discharges

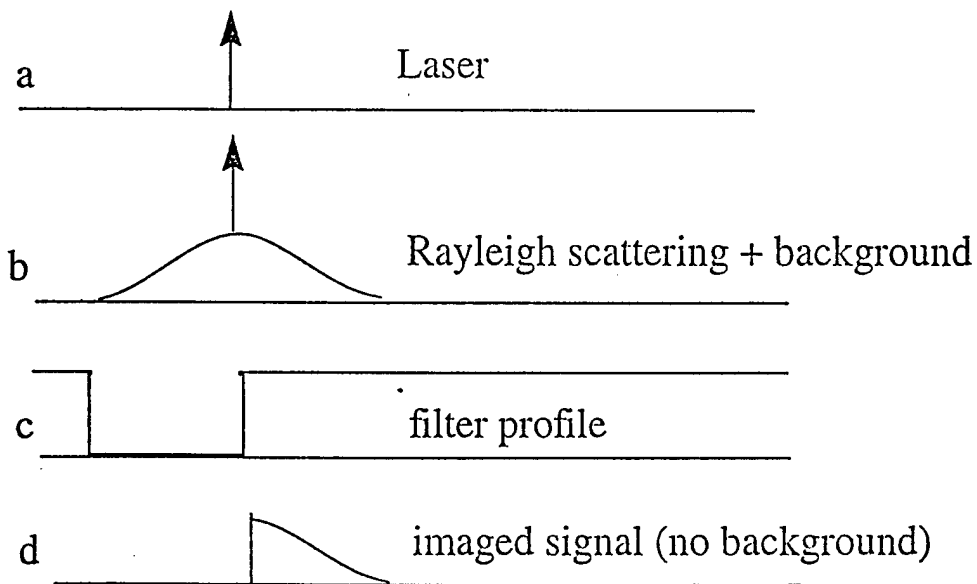
PLASMA TEMPERATURE MEASUREMENT BY FILTERED RAYLEIGH SCATTERING

Rayleigh Scattering

- Total Scattering is Proportional to Density
- Linewidth is proportional to \sqrt{T}
- Signal is weak
- Background scattering is at nearly the same frequency

Filtered Rayleigh Scattering

- Eliminates Background Scattering
- Permits Measurement of Linewidth



FILTERED RAYLEIGH SCATTERING IMPLEMENTATION

- Source

- Tunable Ultraviolet, Injection Locked Laser
- Ti:sapphire with "Ramp and Lock" Technology
(Schwartz Electro-Optics)

- Filter

- Atomic Mercury Vapor
- 2" Diameter Cell Held at 40°C with a
hot water bath (vapor pressure 1 Torr)

- Camera

- UV Sensitive, Intensified CCD (Princeton
Instruments)

SEQUENTIAL RAYLEIGH IMAGES OF MACH 2.5
SHOCKWAVE / BOUNDARY LAYER INTERACTION
AT A 14° WEDGE

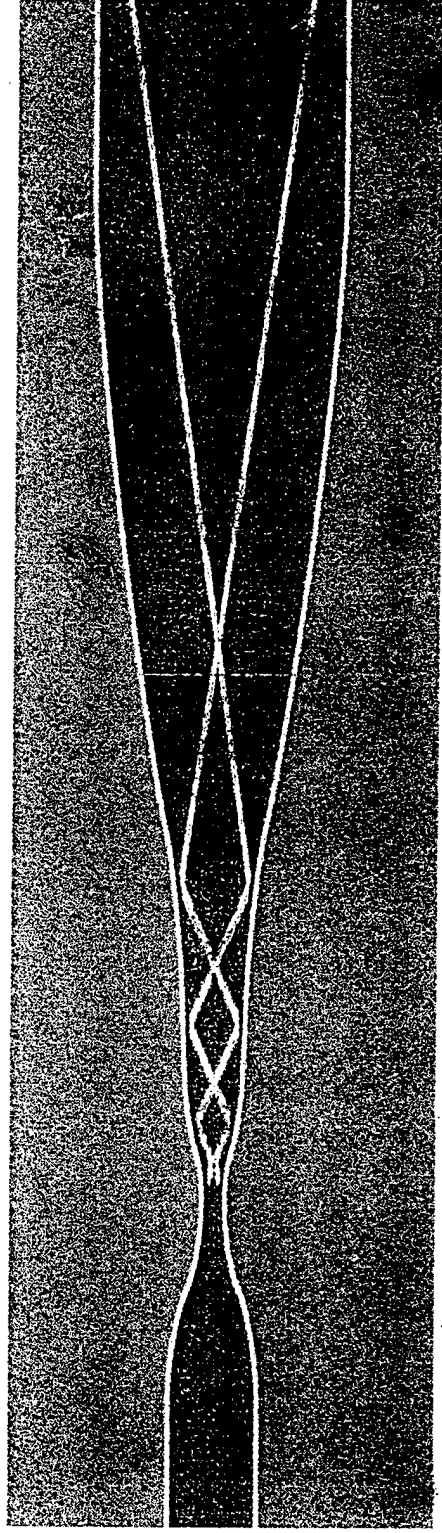


Framing rate is 500,000 images per second

Mariah II

- No wind tunnel can at present be run to accurately simulate flight conditions at higher than Mach 8
 - 240K, (120,000 ft) requires 2800K, 8 atm in plenum
 - NO contamination
 - Low static T or low static P (enthalpy too low or entropy too high)
 - Short time operation
- Radiatively Driven concept adds energy downstream of the throat in the supersonic section
 - Static temperature stays low
 - Low temperature but high pressure in the plenum
 - Concept is driven by lasers or electron beams
 - Demonstrated with 10KW laser in December at Wright Labs
- MHD section is to be added to further accelerate the flow after the Radiative section
 - Reduces the front end pressure requirement
 - Extends the envelop of the tunnel
 - Requires electron beam sustained conductivity
 - Must operate at close to room temperature and at pressures on the order of .1 atm.

Energy Addition by Lasers



RDHWT Review April 23 - 24, 1997

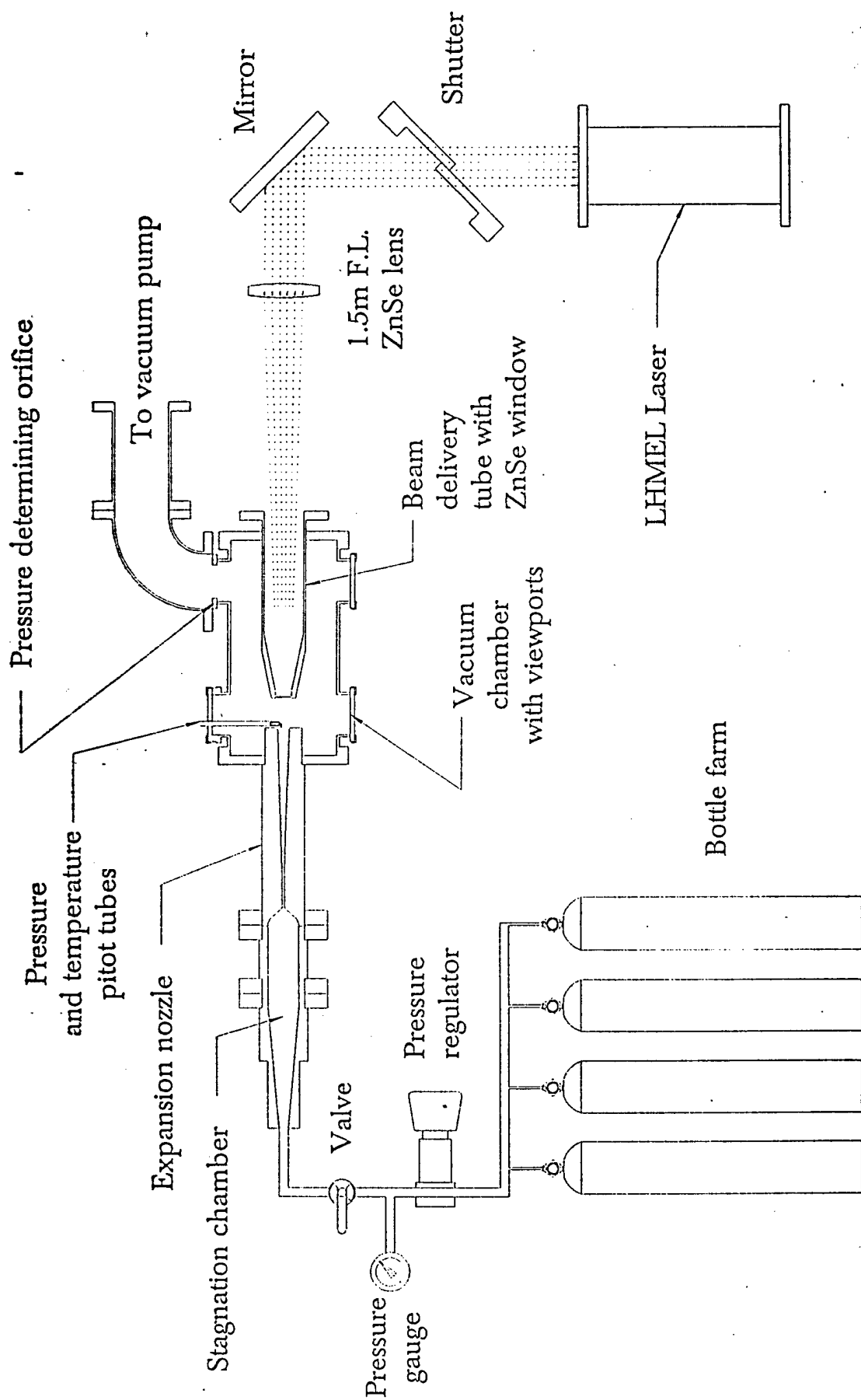
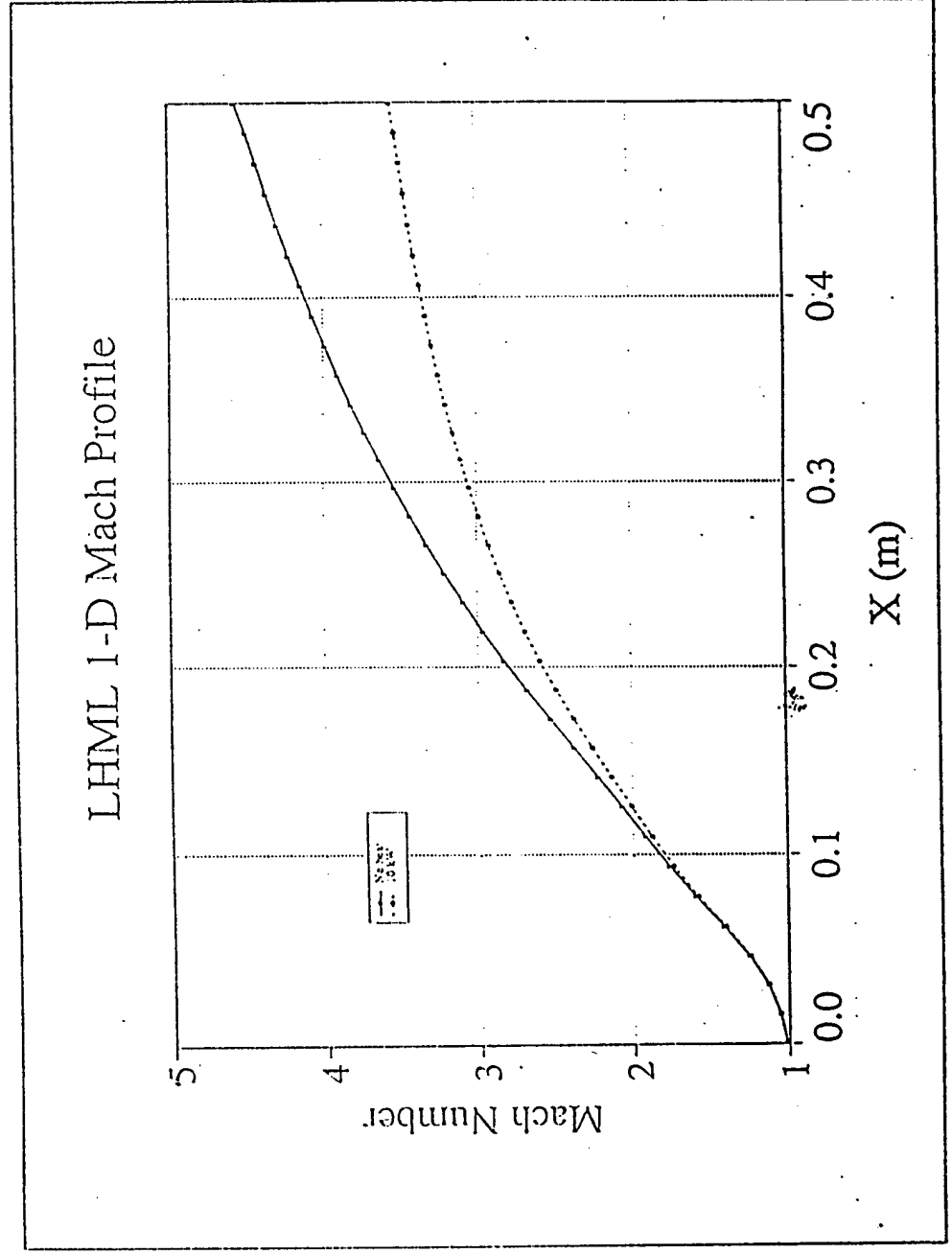


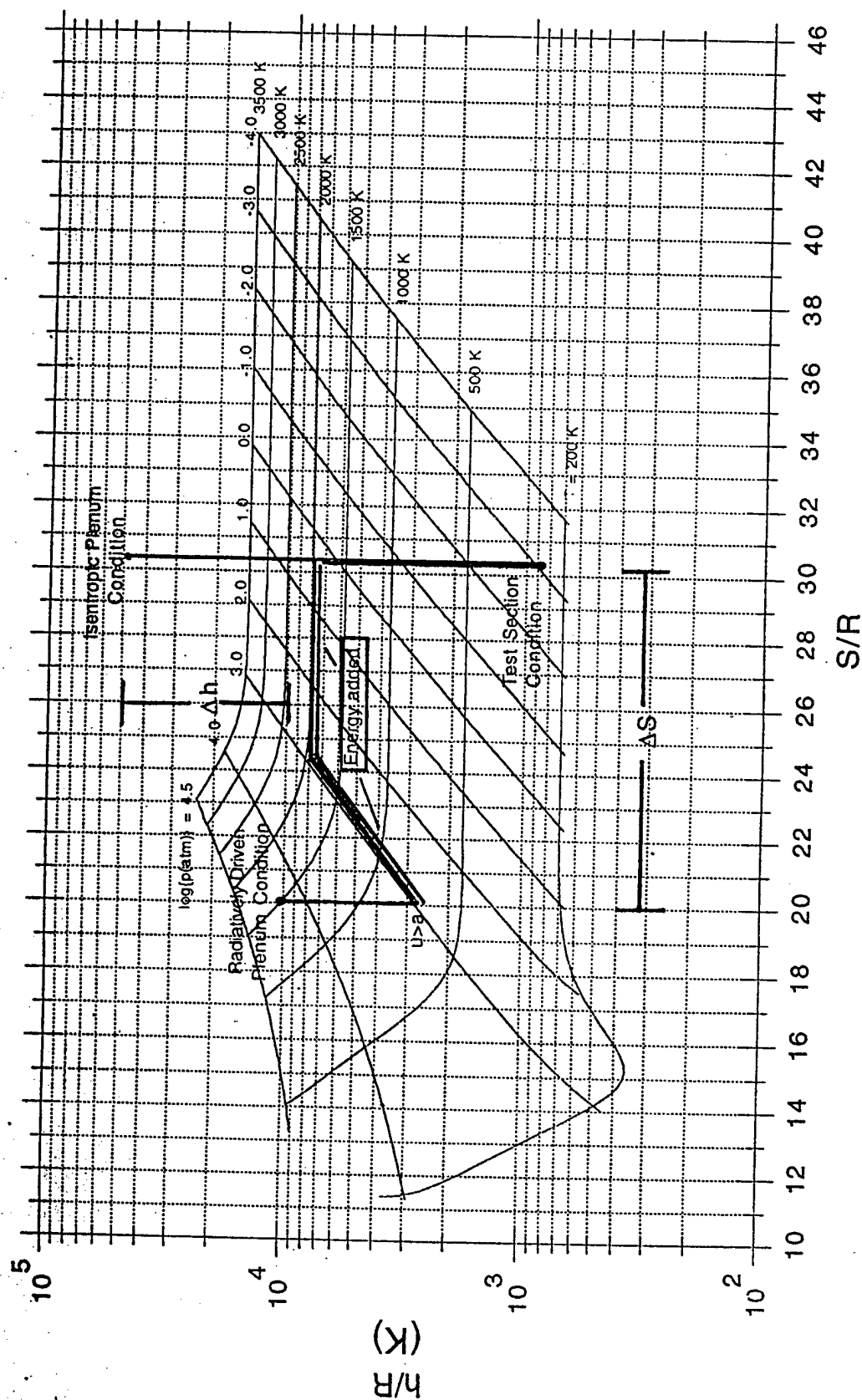
Figure 1. Diagram of 10 kw laser energy addition experiment

CFD - Energy Addition

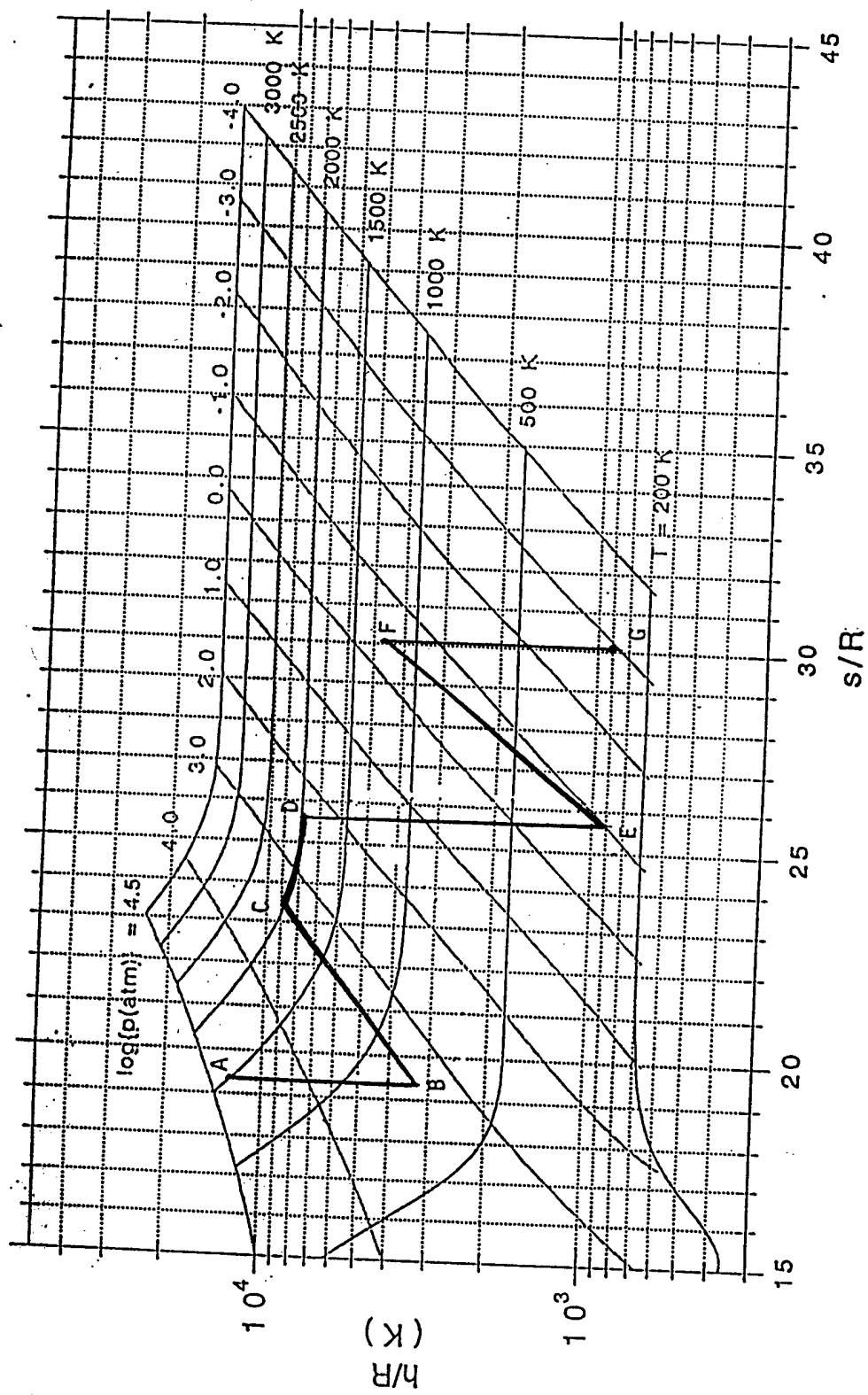
- ◆ At exit $\Delta M \sim 1$



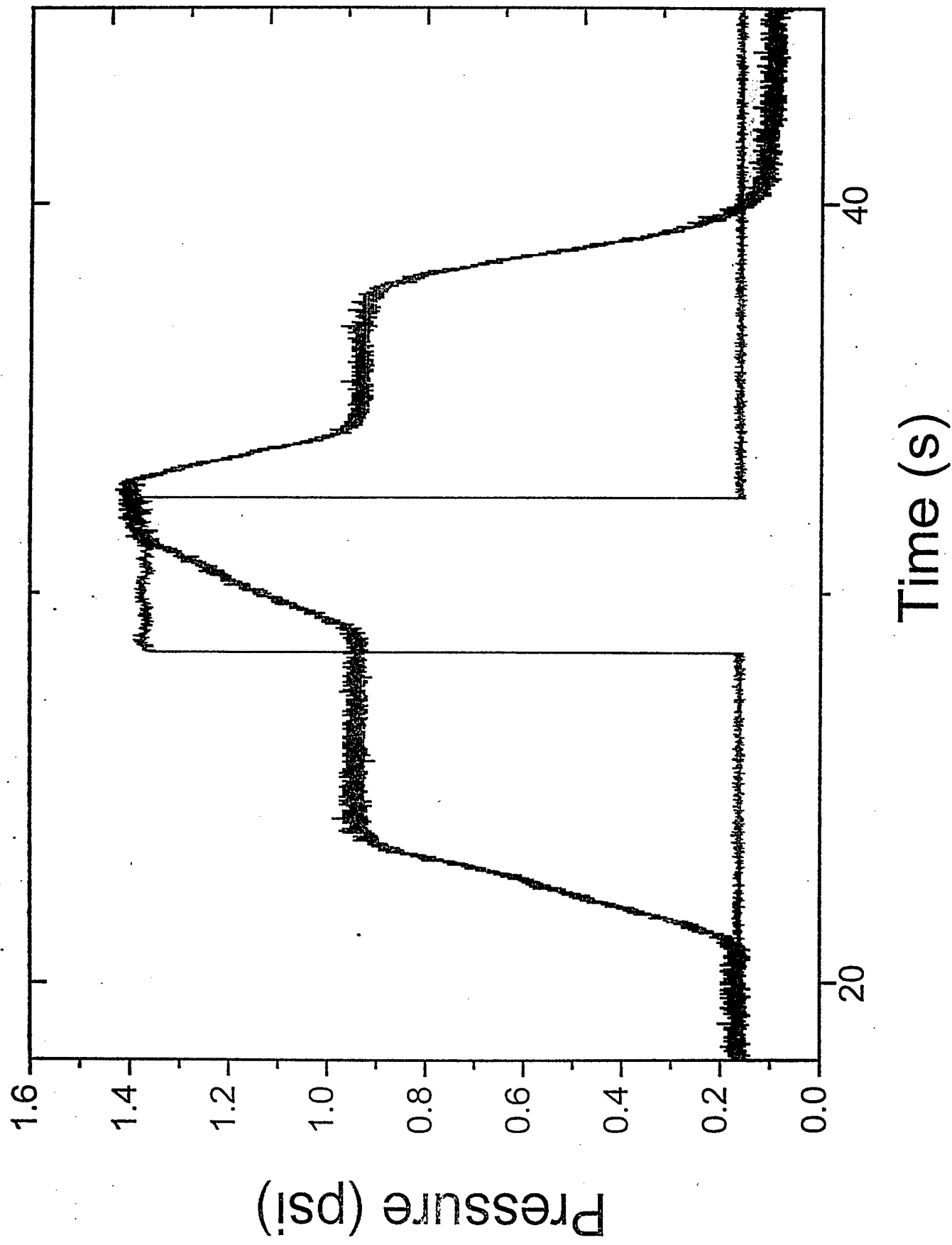
Thermodynamic Comparison of Philosophies



Energy equal to the energy deficit between the two plenum conditions is added along the highlighted path which is determined by the tunnel profile. An effective temperature, $\Delta h/\Delta s$, indicates the mean temperature at which the enthalpy must be coupled. Note that real gas effects are significant in the plenum region so that enthalpy is a function of pressure.



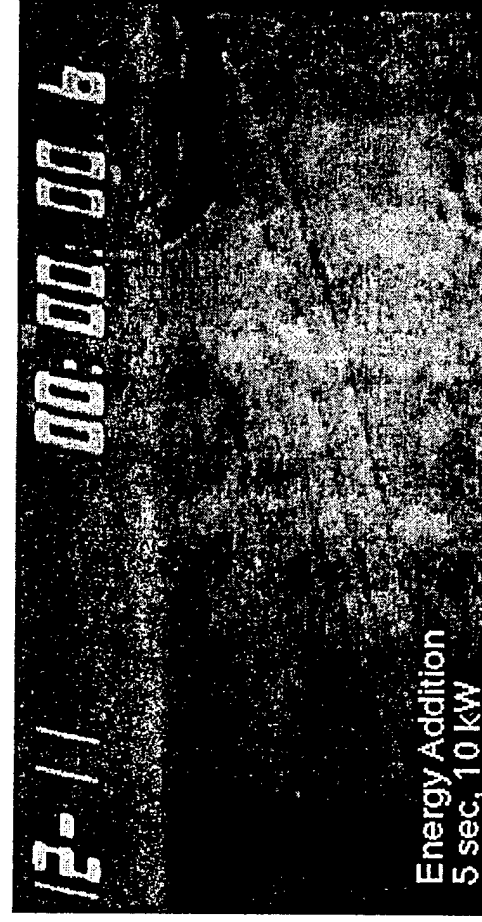
Static 1 inch from exit



Flow Around Probe



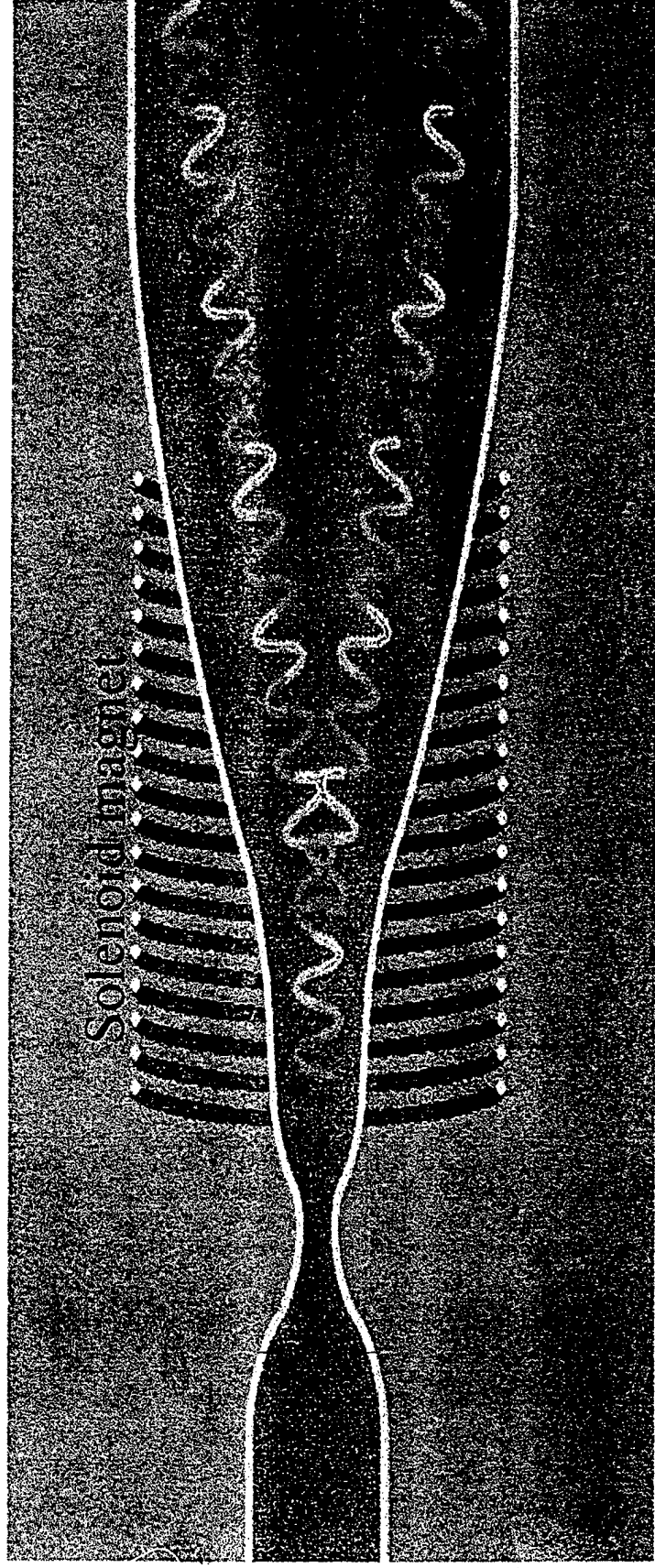
Laser Off
M = 4.3



Laser On
M = 3.9

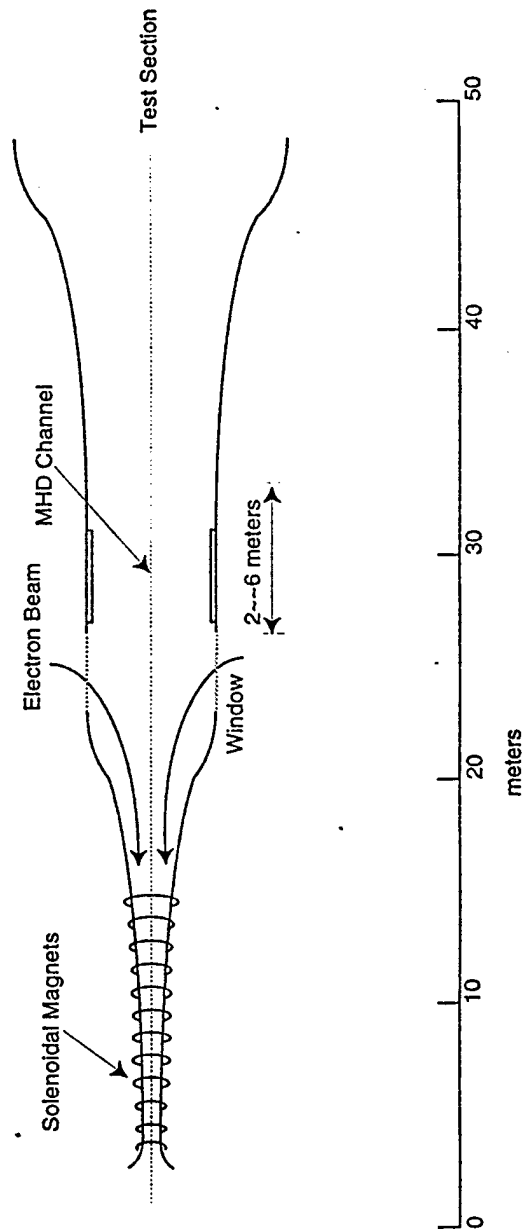
Results verified by Pitot Measurements

Energy Addition by Electron Beams



RDHWT Review April 23 - 24, 1997

Hybrid Hypersonic Wind Tunnel with E-beam Heating and MHD Acceleration Mach 14, 3.0-m Exit Diameter



Thermodynamic limit of RDHWT:

$$\Delta h = T_a \Delta s$$

T_a can't be extremely high (erosion, chemistry);
minimum s is defined by incompressibility;
maximum s is defined by test section requirements.

THERMODYNAMIC ADVANTAGE OF MHD

Total enthalpy augmentation:

$$\Delta h_t = \frac{K}{K-1} T \Delta s$$

where $K \equiv E/(uB) = (\text{Energy added})/(\text{Push work})$

The best thermodynamically:

when $K \rightarrow 1$, Δh_t can be large even for small $T \cdot \Delta s$
(non-entropy-generating energy addition).

However, when $K \rightarrow 1$, $j = \sigma \cdot (E - uB) \rightarrow 0$,
and to add

$$\Delta h_t = \sigma K(K-1) u B^2 L / \rho ,$$

very large conductivity, σ , and/or length, L , would be required

AJAX
Proposed by Russians in 1990
(Vladimir Freistadt -
State Hypersonic Systems Scientific Research Enterprise
St. Petersburg)

- MHD converter in the inlet connected to MHD accelerator in the nozzle to by-pass free stream kinetic energy and reduce the entropy rise in the inlet.

- Reduces the flow to subsonic in the combustor
- MHD conditions almost the same as Mariah II
- Requires some method to sustain conductivity

- Reduction in vehicle drag by cold plasma injection at the nose

- Increase of combustion volume and efficiency within the engine by plasma injection or injection of materials ahead of the fuel injectors

- Reforming of kerosene and water into hydrogen and CO for fuel.

Computational Hypersonics Initiative
in
Air Force Research Laboratory

J. S. Shang
Air Vehicle Directorate
Air Force Research Laboratory
Wright-Patterson Air Force Base, Ohio 45433

Objective

- Rekindle a multidisciplinary computational modeling and simulation research to support the USAF New World Vista Vision.
- Develop an enabling critical simulation technology for aerospace vehicle in hypersonic flight regime.
- Research the potential of electromagnetics/shock interaction as a new flow-field control mechanism.

Scientific "Findings" in Plasma/Shock Interaction

- Appearance of a shock precursor and increase standoff distance of bow shock wave in weakly ionized gas.
- Shock propagation velocity increases and shock front disperses in plasma medium.
- Intermingled reflected compression and rarefaction waves propagation in inhomogeneous plasma media.
- Aerodynamic drag and heat transfer to solid surface are modified by weakly ionized gas.
- Magnetic field suppresses laminar-turbulent transition bypass.

Macroscopic Conservation Equations

$$\begin{aligned}
 & \frac{\partial \rho \alpha_i}{\partial t} + \nabla \cdot (\rho \alpha_i \bar{u} + \rho \alpha_i \bar{u}_i) = \dot{r}_i \\
 & \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \bar{u}) = 0 \\
 & \frac{\partial \rho \bar{u}}{\partial t} + \nabla \cdot (\rho \bar{u} \bar{u} - \bar{\tau}) = \rho \sum \bar{f}_i \\
 & \frac{\partial \rho e}{\partial t} + \nabla \cdot (\rho e \bar{u} + \bar{u} \cdot \bar{\tau} - k \nabla T + \rho \sum \alpha_i h_i \bar{u}_i + \dot{q}_r) + \sum_i \dot{r}_i \Delta h_i^o \\
 & = \rho \sum \alpha_i \bar{f}_i \cdot (\bar{u} + \bar{u}_i)
 \end{aligned}$$

In numerical simulations of hypersonic flows, this system of conservative equations is usually written in strong conservation form.

$$\frac{\partial U}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y} + \frac{\partial H}{\partial z} = 0$$

Arrhenius equation

In order to apply the law of mass action, the rate of reactions is assumed to be independent of whether or not the system is in equilibrium. This commonly accepted assumption is consistent with the local equilibrium approach. The rate constant is given as $K_{c,j} = K_{f,j}/K_{b,j} = \Pi(X_i)''^{\nu_{i,j}} / \Pi(X_i)'^{\nu_{i,j}}$. Only when the gas mixture is in chemical equilibrium, the forward and reverse reactions are in dynamic balance, and the net rate of change in composition vanishes.

$$\left(\frac{dX_i}{dt} \right)_j = (\nu_{i,j}'' - \nu_{i,j}') K_{f,j} \left[\Pi(X_i)'^{\nu_{i,j}} - \frac{1}{K_{c,j}} \Pi(X_i)''^{\nu_{i,j}} \right]$$

The so-called rate constant has been experimentally recognized as

$$K_{c,j} = C \exp \left(-\frac{\epsilon_a}{KT} \right)$$

This is the well-known Arrhenius equation, and the constant ϵ_a is often referred to as the Arrhenius activation energy. This equation has been modified to better fit to measurements as

$$K_{c,r} = CT^\eta \exp \left(-\frac{\epsilon_a}{KT} \right)$$

Internal Degree of Excitation of Gas Medium

The partition function of a microscopic particle is fundamentally important in relating atomic/molecular structure, which influence the energy level, and thermodynamic behavior.

$$Z = \sum_i g_i \exp \left\{ -\frac{\epsilon_i}{kT} \right\}$$

Usually, the coupling of internal degrees of freedom of gas medium is neglected, this assumption leads to the factorization property of partition functions.

$$Z = Z_{trs} \cdot Z_{rot} \cdot Z_{vib} \cdot Z_{el}$$

The energy of different internal degree of excitations is additive, the total internal energy is then found by summing the translational, rotational, vibrational, and electronic modes.

$$E_i = E_t + E_r + E_v + E_e$$

Partition Functions of Internal Degree of Freedom

Translational DOF	Z_{trs}	$= \left(\frac{2\pi mkT}{h^2} \right)^{\frac{3}{2}} V$
Rotational DOF	Z_{rot}	$= \frac{T}{\sigma \theta_r}$
Vibrational DOF	Z_{vib}	$= \frac{1}{1 - \exp \left\{ \frac{\theta_v}{T} \right\}}$
Electronic DOF	Z_{el}	$= g_o + \sum_i g_i \exp \left(-\frac{\theta_{e,i}}{T} \right)$

Shortcomings in Computational Hypersonics

- Inadequate description of transport property.
- Unreliable non-equilibrium kinetic models for vibration-vibration and vibration-translation energy transfer.
- Marginal numerical accuracy and low computational efficiency.
- Sparse or non-existent verification data base.

Langevin's Formula

Mobility of Charged Particles

$$D = \frac{3}{8} \sqrt{\frac{\pi}{2}} \frac{1}{n S_D} \left(\frac{m + M}{m M} k T \right)^{\frac{1}{2}}$$

$$\frac{u}{E} = \frac{3}{8} \sqrt{\frac{\pi}{2}} \frac{q}{n S_D} \left(\frac{m + M}{m M} \frac{1}{k T} \right)^{\frac{1}{2}}$$

Mobility of Heavy Ions

$$D = \frac{3}{8} \sqrt{\pi} L \left(\frac{m + M}{m M} k T \right)^{\frac{1}{2}}$$

$$\frac{u}{E} = \frac{3}{8} \sqrt{\pi} q L \left(\frac{m + M}{m M} \frac{1}{k T} \right)^{\frac{1}{2}}$$

$$L = \frac{1}{\sqrt{2} n S_d}$$

Mobility of Free Electrons

$$\frac{u_e}{E} = \frac{2}{3} \sqrt{\frac{2}{\pi}} \frac{e L_e}{(m k T)^{\frac{1}{2}}}$$

$$L_e = 4 \sqrt{2} L$$

Understanding and Control of Ionized High-Speed Flows

AFOSR Workshop

Plasma Aerodynamics Studies

N. Malmuth, V. Soloviev, H. Hornung, V. Bytchkov
V. Krivstov, A. Konchakov, A. Tseskis and V. Veilikodnyi

February 26, 1998

Other Team Members

- W. Beaulieu, Boeing Aircraft and Missile Systems
- P. Bellan, Caltech
- A. Fedorov, Moscow Institute of Physics and Technology
- I. Goldberg, Rockwell Science Center
- A. Klimov, Moscow Technical Club
- K. Lee, Rockwell Science Center
- S. Leonov, Moscow Technical Club
- D. Ota, Rockwell Science Center
- S. Palinswamy, Metacomp
- S. Ramakrishnan, Rockwell Science Center

Plasma Aerodynamics

Objectives/Approach

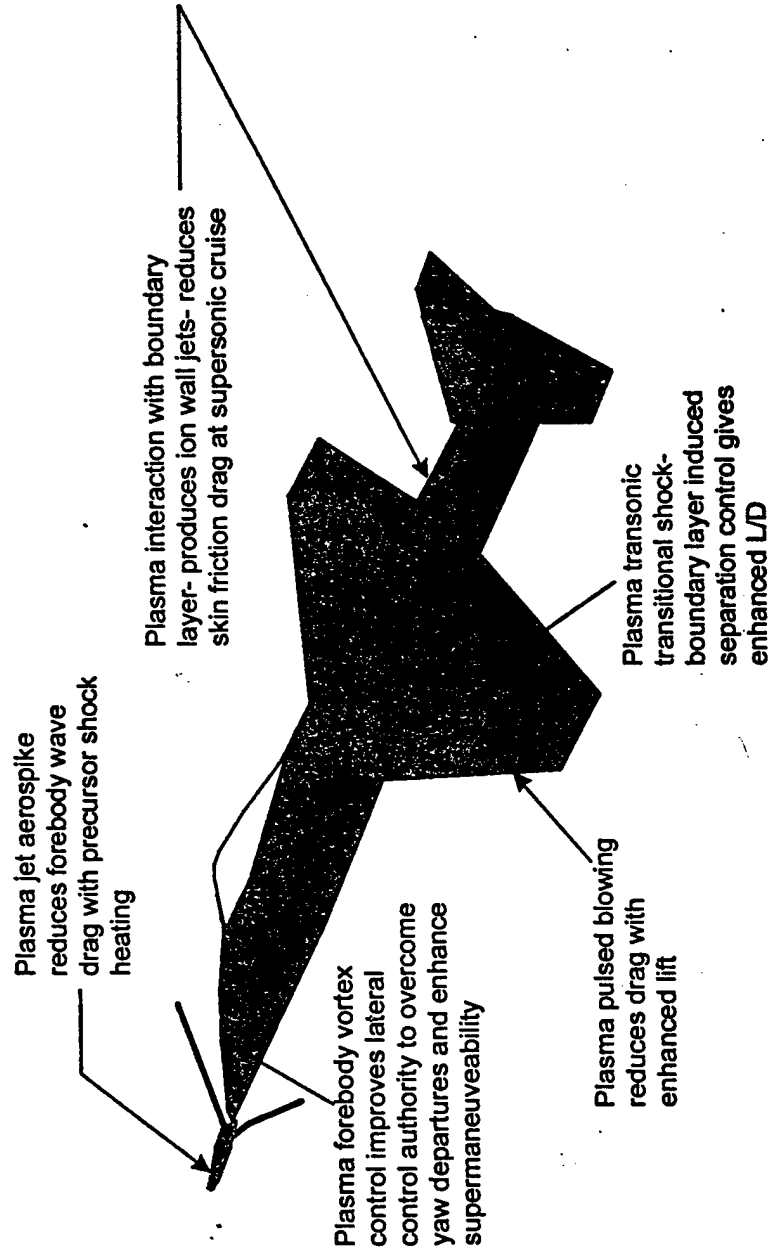
- Program Objectives
 - Determine basic physical processes of plasma aerodynamic augmentation
 - Develop analytical and computational models of these processes
 - Provide links with experiments
 - F-15 flight test
 - Ground and on-board flight instrumentation
 - Plasma generator technology
 - Wind tunnel , ballistic range, discharge tube and other ground tests
 - coupling with analytical model development, e.g. cross-validations
 - design and interpretation of experiments

Objectives/Approach (cont'd)

- Approach
 - Study importance of key physical mechanisms in flow such as:
 - plasma energy addition to flow such as Joule heating
 - anomalous dispersion
 - ion-acoustic waves
 - non-equilibrium phenomena
 - second viscosity and other transport parameter modification
 - electromagnetic effects such as induced B fields and Lorentz forces
 - Use solutions of unit problems such P1-P4 (for which limited experimental databases exist) to isolate these important mechanisms
 - Interface with experiments
 - Design new experiments
 - Compare evolving theoretical models with previous datasets

Supercruise Fighter

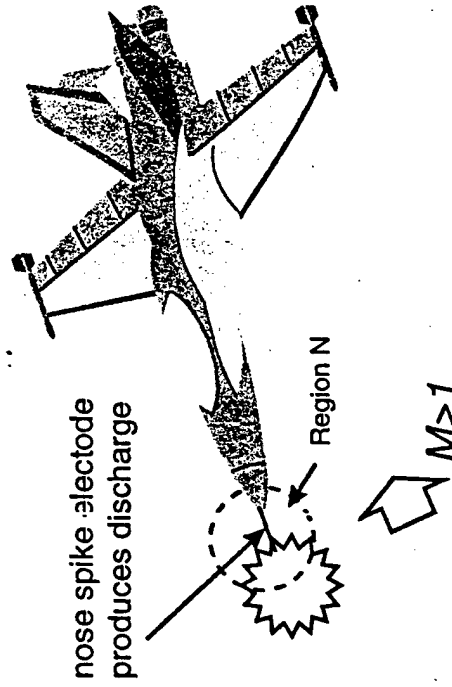
Plasma Aerodynamic Enhancements



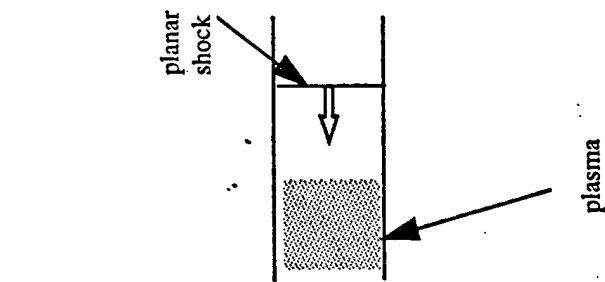
Noseboom Plasma Flow Control

(Problem P4)

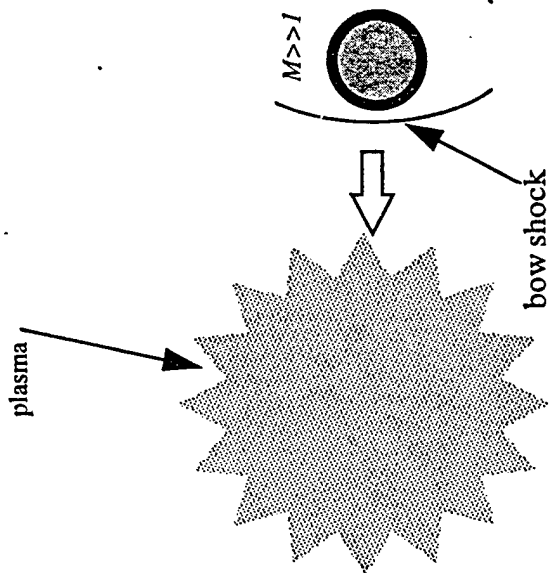
- Basic hypotheses:
 - dissipative processes in plasma lead to
 - Joule heating that reduces pressure drag
 - control of nose separation and nose shocks
- Problem is a useful departure point for treatment of:
 - Problem 3: erosive plasma + RF discharge on F-15
 - 1-D shock structure
 - hypersonic applications
- P4 study useful since experimental dataset available to test models



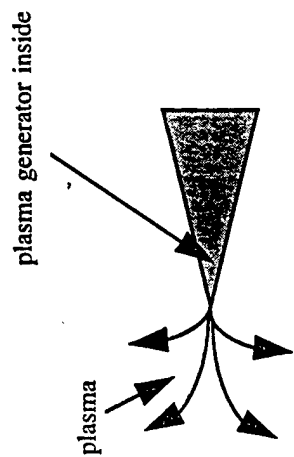
Problems



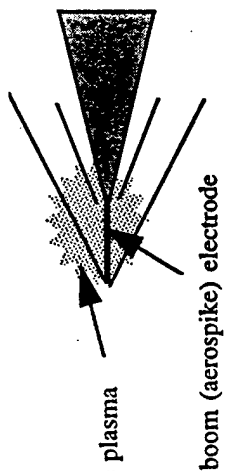
Problem 1



Problem 2



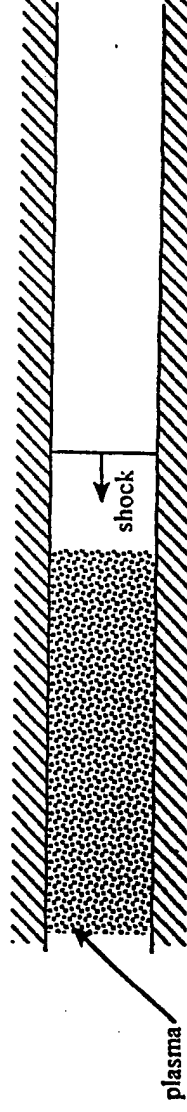
Problem 3 - (F-15)



Problem 3a - (F-15)

Plasma Shock Structure

- Modify 1-D Navier Stokes equations to model
 - electric field and other plasma terms
 - second viscosity
 - relaxation
 - anomalous dispersion
- Examine scaling of shock thickness with strength from Russian experiments



1-D shock propagating into a plasma

Perfect Gas Shock-Layer Problem

Equations of Motion

Continuity

$$\frac{d}{dx}(\rho u) = 0$$

Momentum

$$\rho u \frac{du}{dx} + \frac{dp}{dx} = \frac{d}{dx} \left(\mu'' \frac{du}{dx} \right)$$

Energy

$$\rho u \frac{dh}{dx} - u \frac{dp}{dx} = \frac{d}{dx} \left(\frac{\mu''}{Pr''} \frac{dh}{dx} \right) + \mu'' \left(\frac{du}{dx} \right)^2$$

$\mu'' \approx 2\mu + \lambda$, $\mu \equiv$ shear viscosity, $\lambda \equiv$ "second" viscosity, $Pr'' \equiv$ Prandtl Number

Boundary conditions

$$\frac{du}{dx}, \frac{dh}{dx} \rightarrow 0, \text{ as } x \rightarrow \pm \infty$$

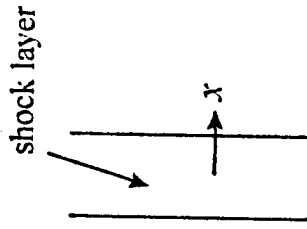
Solution for Shock Thickness

$$\delta = \frac{32 \left(\gamma + (\gamma - 1) \left(\frac{1}{Pr''} - 1 \right) \right) V''}{3(\gamma + 1)(V_f - V'_i)}$$

$\delta \equiv$ viscous shock layer thickness

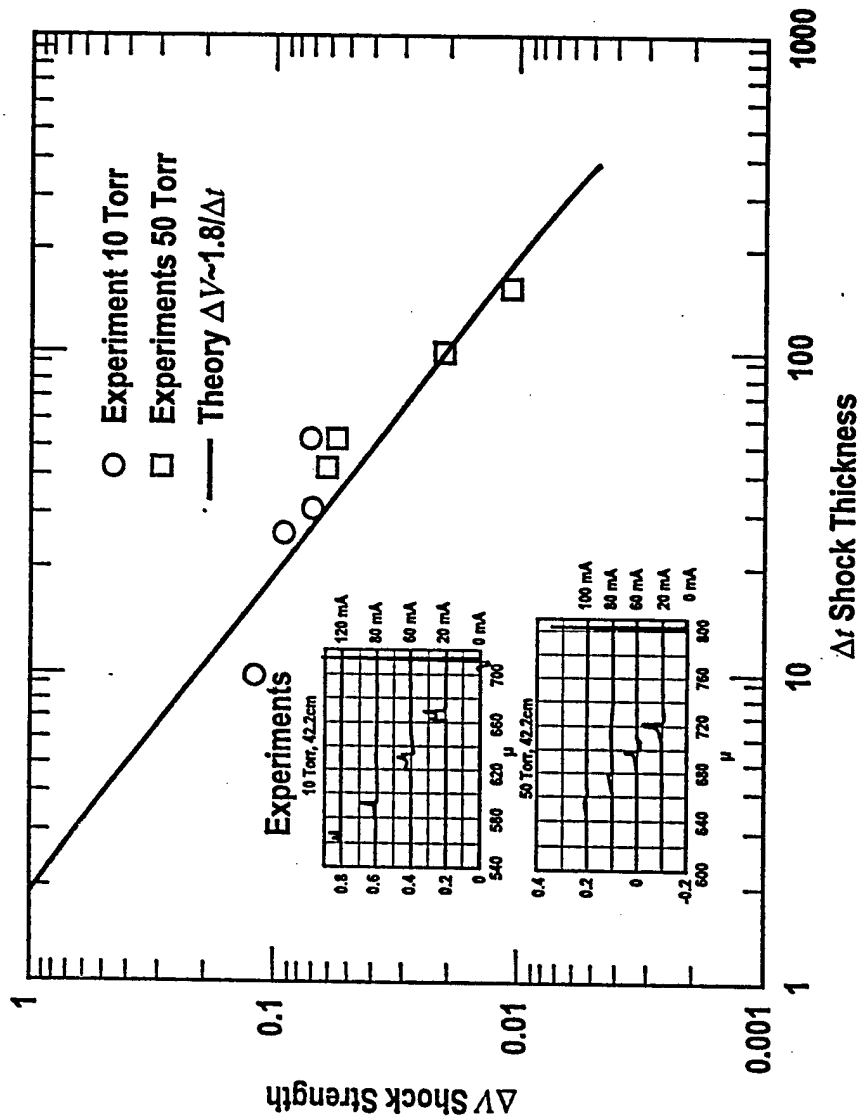
$V_f - V'_i \equiv$ shock strength

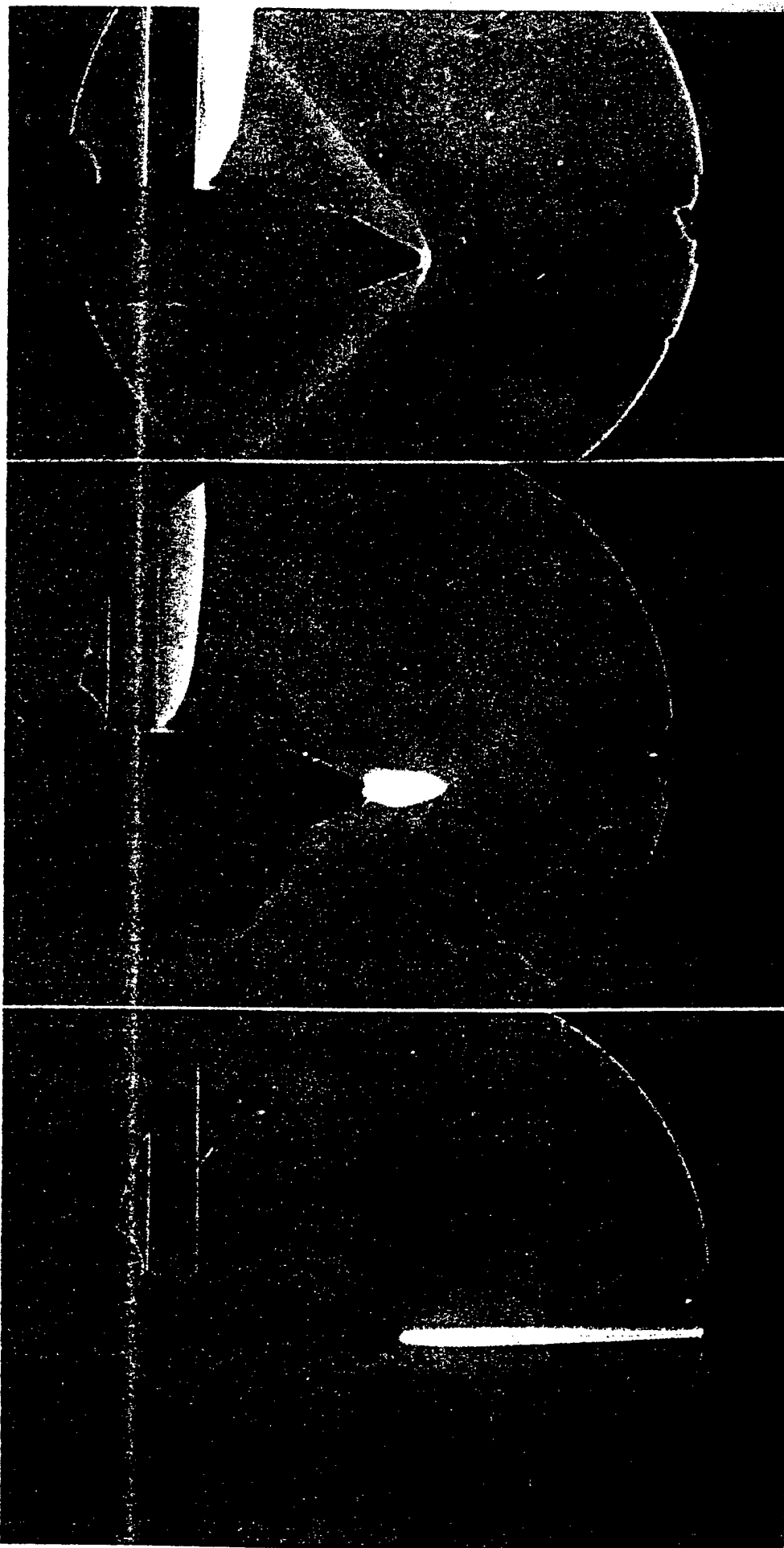
$\gamma \equiv$ specific heat ratio



Scaling of Shock Attenuation with Thickness in a Plasma

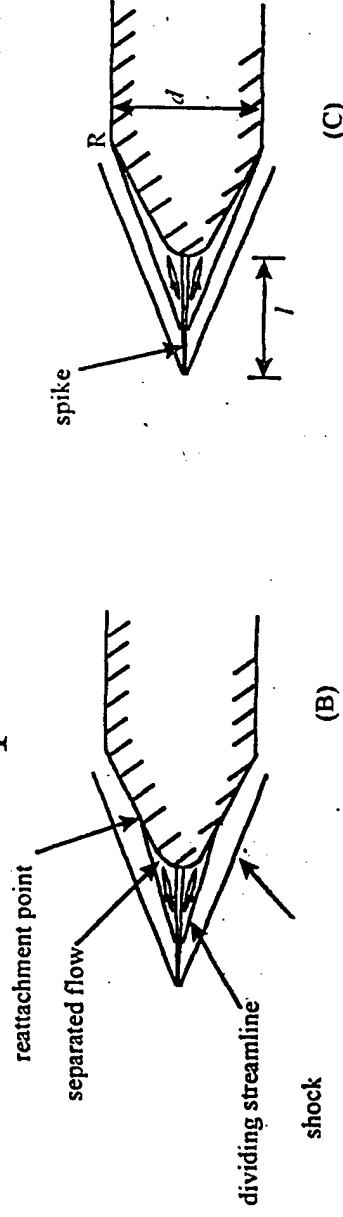
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Drag Reduction Mechanisms

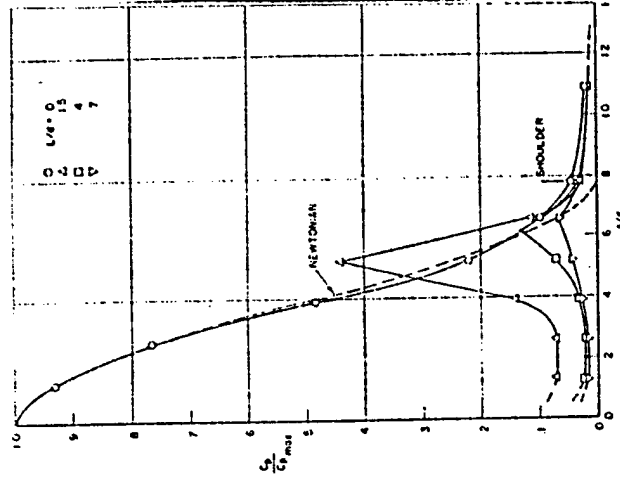
- Plasma jet aerospike extension
 - aerospike reduces drag by making a shallow oblique shock out of blunt nose detached almost normal shock
 - creates low pressure separation in front of blunt nose to give a net suction thrust increment
- Transverse shock due to plasma heating leading to rarefaction of separation region
- Interaction of separation and transition over the aerospike



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Flow Configurations

Aerospike Effect on Pressures



Bogdanoff and Vas JAS 1959

- Spike produces peak in pressures near reattachment point
- Peak attenuates with increasing spike length reducing drag
- Needs to be traded against high heat transfer near peak
- Plasma heating can affect reattachment and therefore pressure peak

Estimate of Drag Reduction

Approximate formula based on Newtonian on blunt nose and cone part

$$C_p = 2 \left(\sin^2 \varepsilon + \frac{1}{\gamma M_\infty^2} \right) (1 - \alpha^2) + \frac{P_{\text{plateau}}}{q} \alpha^2 - \frac{2}{\gamma M_\infty^2} \left(1 - \left(\frac{r_{\text{base}}}{r_d} \right)^2 \right)$$

$P_{\text{plateau}} \equiv$ pressure in separation region

$$r_d \equiv \frac{d}{2}$$

$$\alpha \equiv \frac{r_j}{r_d}$$

$r_j \equiv$ radius at junction of spherical nose tip with cone portion

$\varepsilon \equiv$ cone semiapex angle

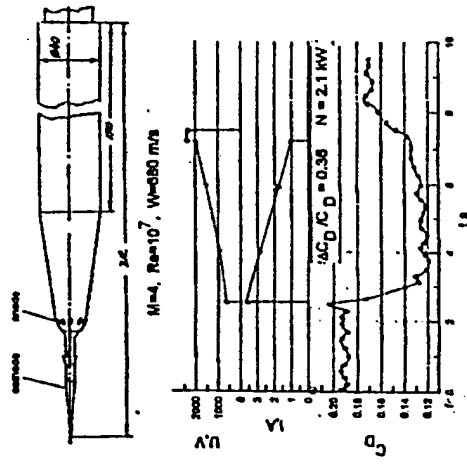


Figure 3 Wind Tunnel Experiments of the Electric Discharge Influence on Drag at TAT

	Experiment	Estimated	Remarks/assumptions in separation zone
current off	.19	.216	plateau pressure=1/2 normal shock value
current on	.12	.07	vacuum due to plasma

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Plasma On

5/ 6/97 STATIC PRESSURE COLOR PANELS 6:30:58
160630 0.67651+03 0.2001+000.404E+03

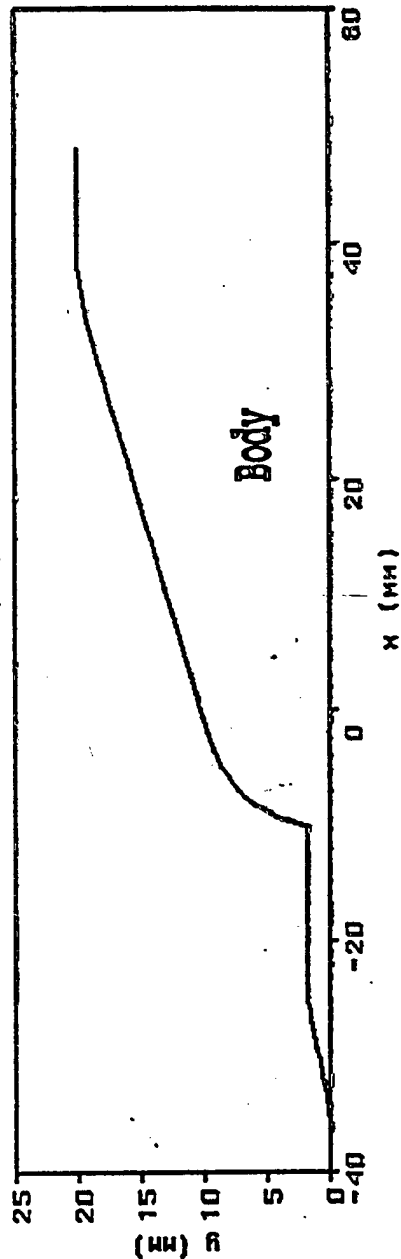
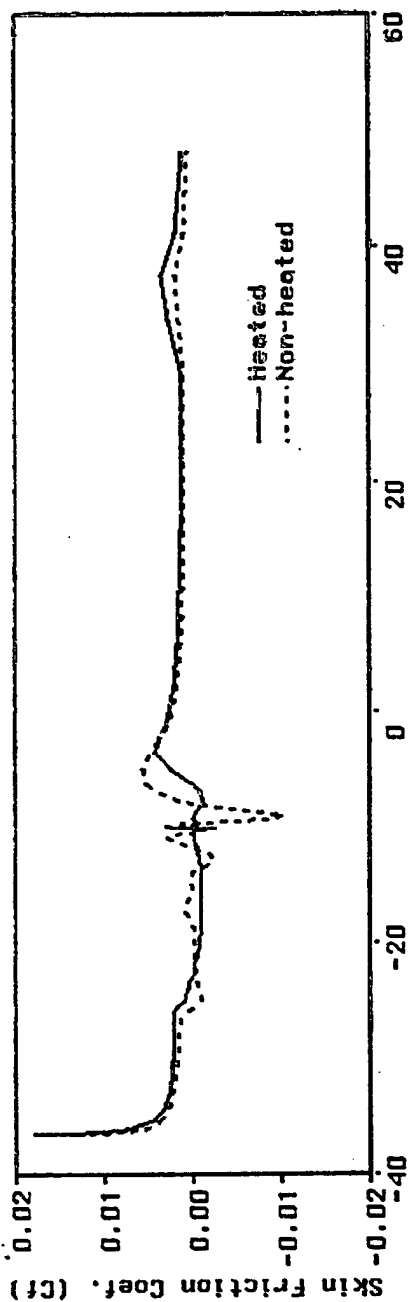
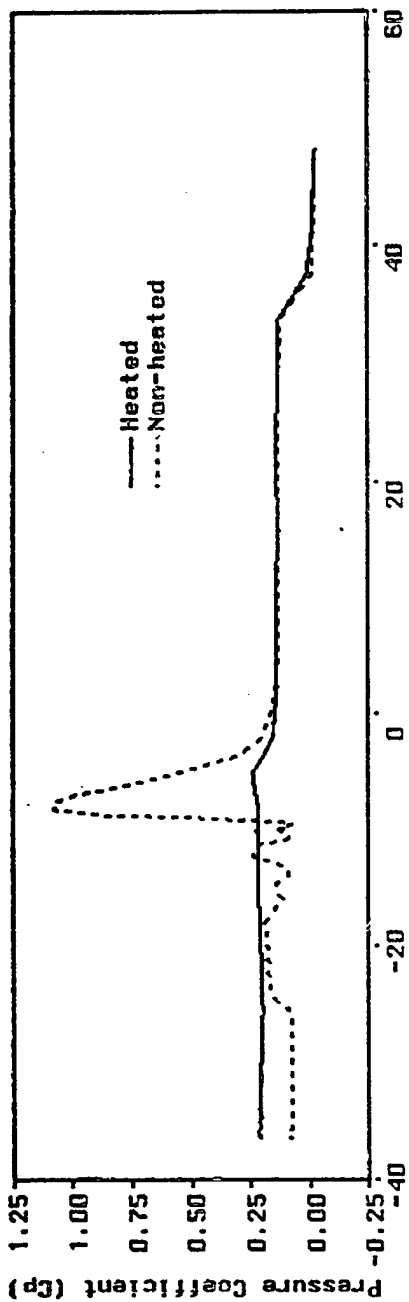
11.000000
12.600000
11.200000
9.80000000
8.40000000
7.00000000
5.60000000
4.20000000
2.80000000
1.40000000
0.00000000

Plasma off

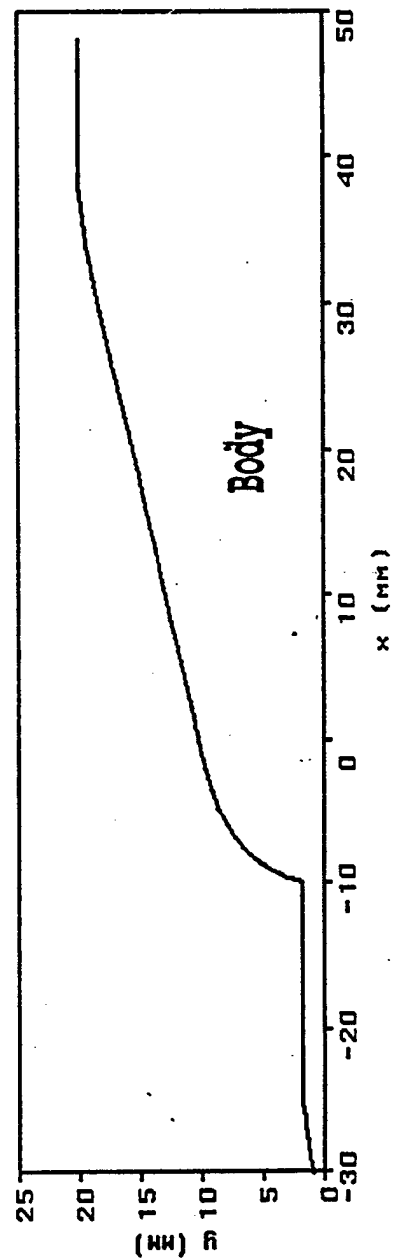
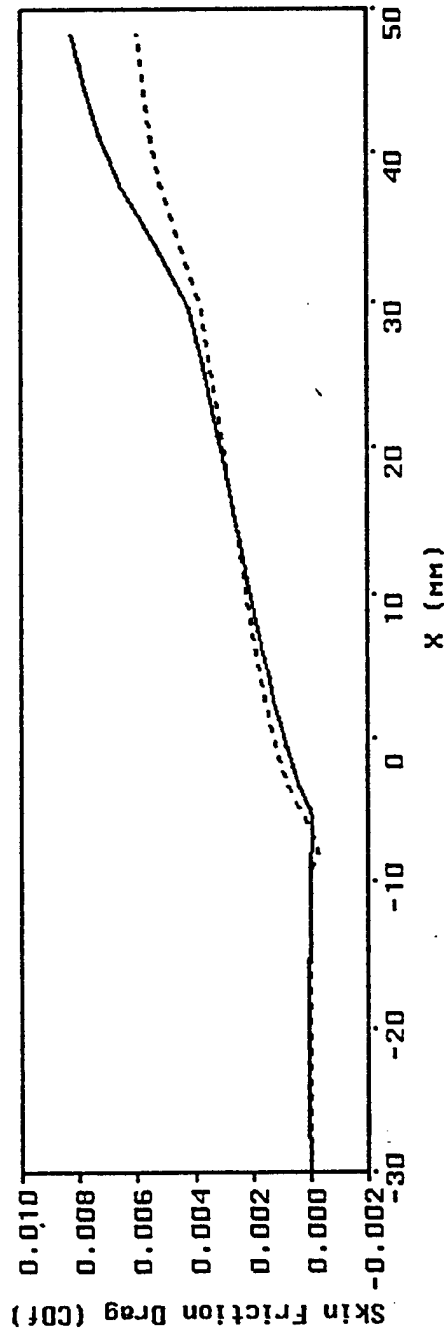
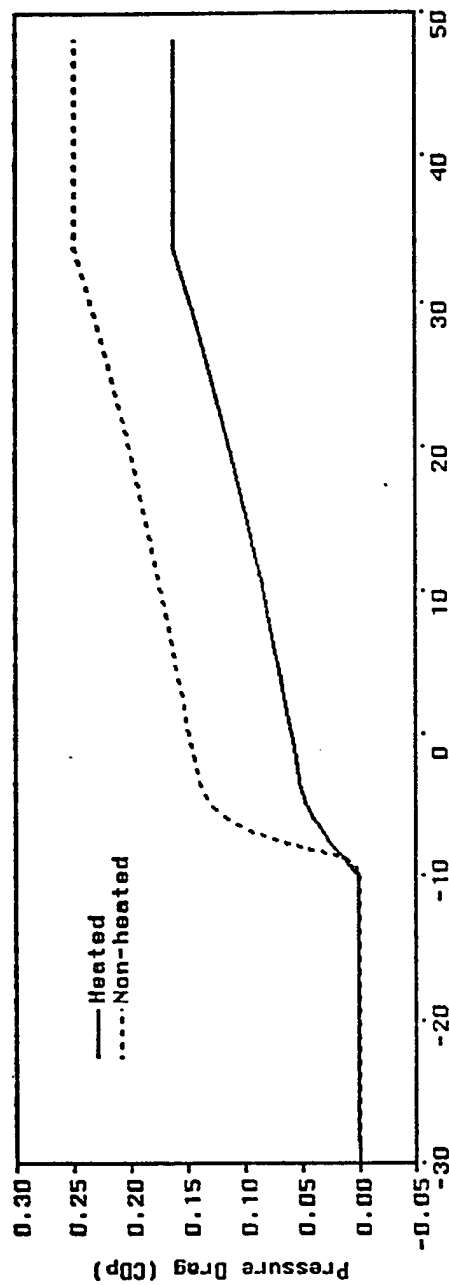
5/ 6/97 SHUTTLE PRESSURE COLOUR PANELS 6:30:50
160630 0.62651 +03 0.2000 +000. 40.01 +03

11.000000
12.500000
11.200000
9.800000
8.100000
7.000000
5.600000
4.200000
2.800000
1.400000
0.000000

Pressure and Skin Friction Distributions With Plasma Heating



Cumulative Pressure and Skin Friction Drag with Plasma Heating



Comparison of Predicted Drags With Russian Experiments

	Rockwell Science Center Computation*	Russian Experiment
C_D (Plasma off)	0.254	0.220
C_D (Plasma on)	0.170	0.180
$\Delta C_D / C_D$	0.33	0.18

*Laminar Navier Stokes model with plasma power uniformly distributed over spike electrode surface

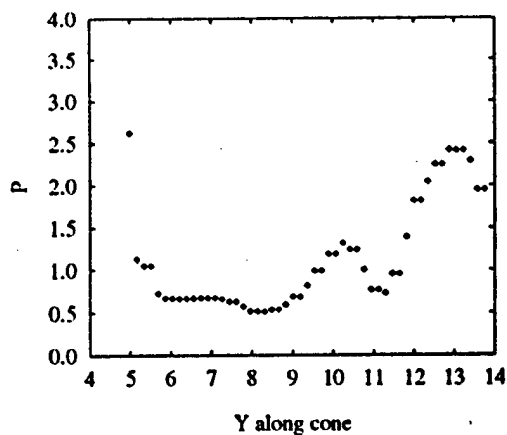
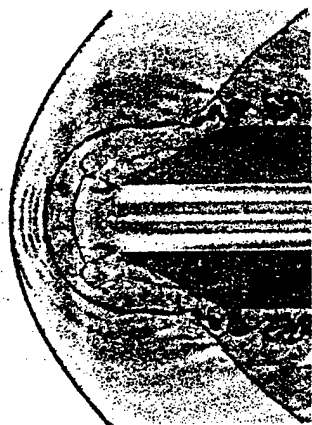
- Discrepancies above within experimental errors
- Heat source model may give dominant physics of spike electrode problem
- Computed relative drag changes agree with experimental order of magnitude

Forebody drag of a cone-cylinder with counterflow jet in supersonic flow

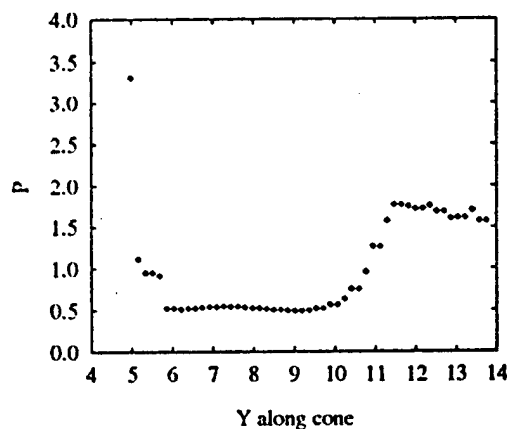
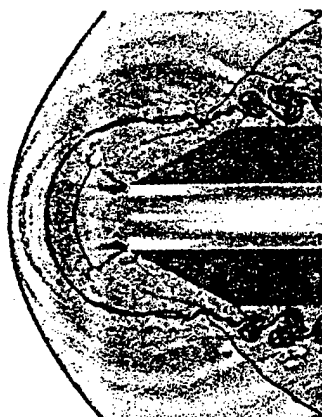
Temp_techarea_iv_Nov 11, 12

- Objectives
 - Study competition of jet momentum drag with surface pressure drag
 - Study basic physical mechanisms
 - Relate to plasma jet effects

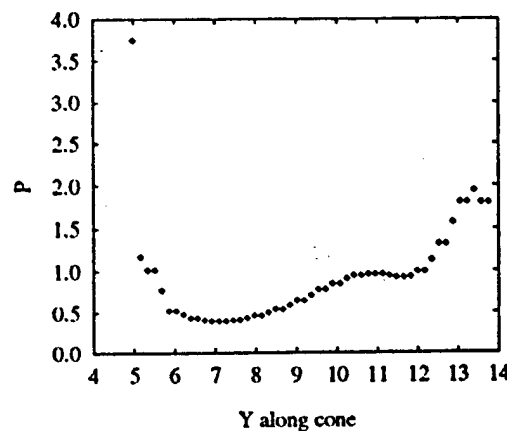
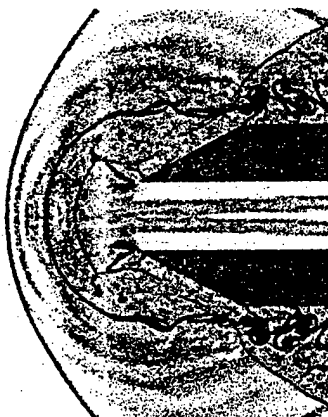




$$p_4/p_\infty = 15.0, C_{D_e} = 0.395, C_{D_i} = 0.462, C_D = 0.857$$



$$p_4/p_\infty = 18.0, C_{D_e} = 0.342, C_{D_i} = 0.553, C_D = 0.895$$



$$p_4/p_\infty = 21.0, C_{D_e} = 0.312, C_{D_i} = 0.646, C_D = 0.957$$

Counterflow jet, $M_\infty = 2.0$, $T_4/T_\infty = 10$, $\gamma = 1.4$.

Forebody drag of a cone-cylinder with counterflow jet in supersonic flow

Temp_techarea_jiv_Nov 11, 12

- Flow field features
 - Small pressure ratios < 12 , (subsonic jets)
 - jet insufficiently powerful to counter freestream, contact surface is an effective blunt body
 - leads to saddle point singularity from which contact interface issues
 - jet separation over body causing a low pressure region giving a thrust
 - Large pressure ratios > 12 , (supersonic jets)
 - Goes through normal shock prior to impingement with freestream
 - Free shear layer stagnates on shoulder, leading to eddies, baroclinic vorticity, multiple secondary shocks and instabilities

Forebody drag of a cone-cylinder with counterflow jet in supersonic flow

Temp_techarea_jiv_Nov 11, 12

- Conclusions
 - Two competing tendencies
 - Jet momentum flux- increases drag
 - Pressure thrust on forebody-decreases drag
 - Drag can be lower than the forebody drag of an equivalent sharp cone or cone frustum
 - Minimum drag occurs when the jet to freestream pressure ratio is approximately 11



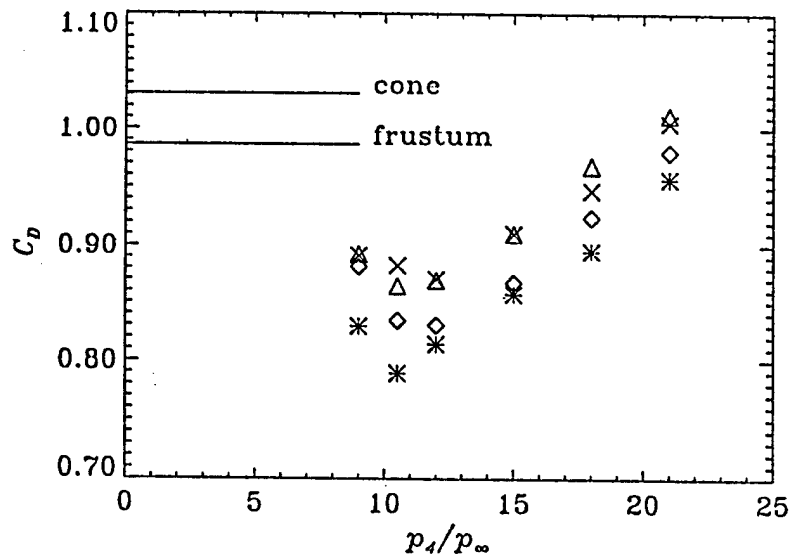


Figure 7: Forebody drag coefficient as a function of p_4/p_∞ for different values of T_4/T_∞ as follows: crosses:1, triangles:3, diamonds:6, asterisks:10. The forebody drag coefficients of the sharp cone and the cone frustum are shown as lines for reference. $M_\infty = 2$, $\gamma = 1.4$

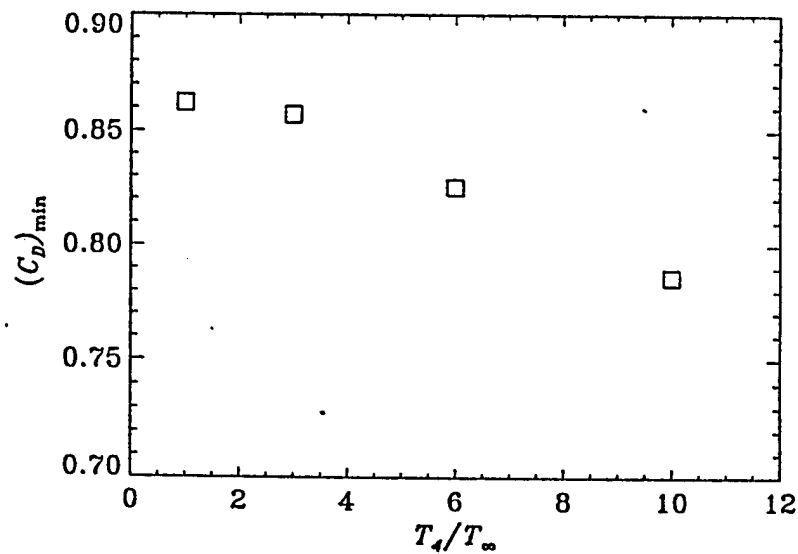


Figure 8: The minimum value of the forebody drag coefficient as a function of T_4/T_∞ . $M_\infty = 2$, $\gamma = 1.4$

Propagation of 1-D Shock Waves Through Weakly Ionized Plasmas

V.R.Soloviev, V.M.Krivtsov, A.M.Konchakov
Moscow Institute of Physics and Technology, Russia

N.Malmuth
Rockwell Science Center, CA, USA

Main topics of the model

- Hugoniot relations on a shock wave (SW) in a weakly ionized plasma
- Estimations of the energy stored in different excited states for glow discharge plasma
- The existence of high situated metastable states in Ar and N₂ , which serve as a 'new ground state' for higher states excitation by electron impact
- Highly excited atomic and/or molecular states store sufficient energy to produce SW acceleration and attenuation
- Inclusion of highly excited atom energy release behind the SW front dramatically improves agreement of theory with experiment for 1-D shock penetrating into a plasma and hypersonic sphere entering a plasma

Hugoniot relations on a shock wave (SW) in a weakly ionized plasma

A set of gas mass, momentum and energy conservation equations in SW coordinates

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial \xi} = 0,$$

$$\frac{\partial(\rho(u+D))}{\partial t} + \frac{\partial}{\partial \xi}(\rho u(u+D) + p) = \frac{\partial}{\partial \xi} \left[\frac{4}{3} \mu \frac{\partial u}{\partial \xi} \right] + f_{\xi},$$

$$\begin{aligned} \frac{\partial}{\partial t} \left[\rho \left(h + \frac{(u+D)^2}{2} \right) - p \right] + \frac{\partial}{\partial \xi} \left[\rho u \left(h + \frac{(u+D)^2}{2} \right) \right] = \frac{\partial}{\partial \xi} \left[\frac{\lambda}{c_p} \frac{\partial h}{\partial \xi} \right] + \\ + \frac{4}{3} \mu \frac{\partial^2}{\partial \xi^2} \left(\frac{(u+D)^2}{2} \right) + f_{\xi}(u+D) + Q_r \end{aligned}$$

$$h = c_p T_a = \frac{\gamma}{\gamma - 1} \frac{p}{\rho},$$

ρ, p, h are density, pressure and enthalpy of the gas; v is its velocity;

λ, μ are thermal conductivity and dynamic viscosity coefficients;

c_p, γ are specific heat at a constant pressure and the ratio of specific heats;

D is the SW velocity;

The f_{ξ} and Q_r terms describe the plasma influence on the gas.

Hugoniot relations

$$\rho_1 u_1 = \rho_0 D,$$

$$\rho_1 u_1^2 + p_1 = \rho_0 D^2 (1 - \varepsilon_{u1}) + p_0,$$

$$h_1 + \frac{u_1^2}{2} = h_0 (1 + \varepsilon_h) + \frac{D^2}{2} (1 - 2\varepsilon_{u2}),$$

where

$$\varepsilon_{u1} = \frac{1}{\rho_0 D^2} \int_{-\infty}^{\infty} f_{\xi} d\xi, \quad \varepsilon_{u2} = -\frac{1}{\rho_0 D^3} \int_{-\infty}^{\infty} f_{\xi} u d\xi, \quad \varepsilon_h = \frac{1}{\rho_0 D h_0} \int_{-\infty}^{\infty} Q_r d\xi$$

- To produce a plasma effect on SW propagation it is necessary ε_{u1} , ε_{u2} , or ε_h to be of the order of 1.

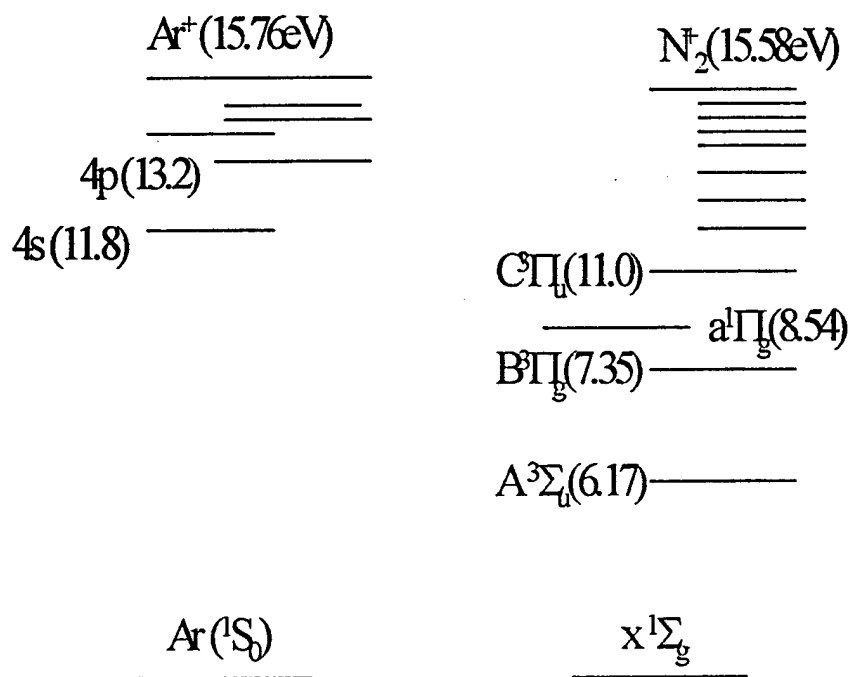
The typical cold glow discharge plasma parameters in SW - discharge interaction experiments

gas pressure (gas density)	$p \approx 3 - 30 \text{ Torr } (N \approx 10^{17} - 10^{18} \text{ cm}^{-3})$
gas temperature	$T \approx 300 \text{ K}$
current density	$j \approx 1 - 100 \text{ mA/cm}^2$
electric field strength	$E \approx 100 \text{ V/cm}$
E/N value	$(2 - 10) \times 10^{-16} \text{ V} \times \text{cm}^2$
discharge specific power	$W \approx 0.1 - 10 \text{ W/cm}^3$
electron temperature	$T_e \approx 1 - 3 \text{ eV}$
electron density	$n_e \approx 10^{10} - 10^{12} \text{ cm}^{-3}$
metastable atom (or molecule) density	$N_m \approx 10^{11} - 10^{13} \text{ cm}^{-3}$

The energy stored in different excited states

- freestream gas enthalpy $h_0 = N c_p T \sim 10^{16} \text{ eV/cm}^3$
- ionization $n_i E_i \sim 10^{12} \text{ eV/cm}^3$, $\epsilon_h = n_i E_i / N c_p T \sim 10^{-4}$
- metastable atoms (or molecules) $N_m E_m \sim 10^{14} \text{ eV/cm}^3$, $\epsilon_h = N_m E_m / N c_p T \sim 10^{-2}$
- specific discharge energy supply
during the time of unit length SW pass $\epsilon_h = W \times 1 \text{ cm} / D N c_p T \sim 10^{-2} - 10^{-1}$
- the vibrational energy is shown to be unsuitable to explain the SW anomalous propagation effects because of large vibrational-translational relaxation time $\tau_{VT} \sim 10^{-3} \text{ s}$

The scheme of Ar and N₂ electronic excited states



Ar(4s) and N₂(A³Σ) are the metastable states

The Ar metastable state quenching and building up

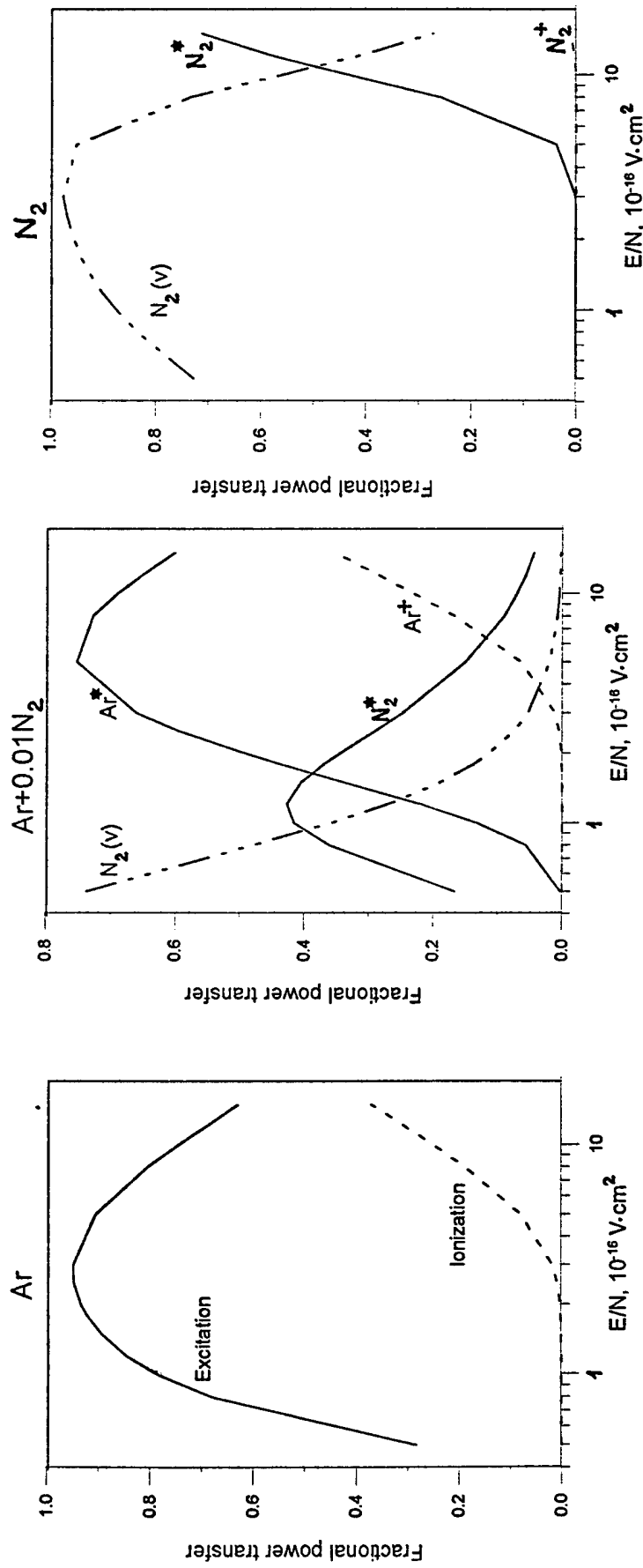
Process	Rate constant	Quenching time for p=10 Torr, $n_e=10^{11}\text{cm}^{-3}$ and 1% N_2 diluent in Ar
$\text{Ar}(4s) + 2\text{Ar} \rightarrow \text{Ar}_2^* + \text{Ar}$	$10^{-32} \text{ cm}^6/\text{s}$	0.8 ms
$\text{Ar}(4s) + e \rightarrow \text{Ar} + e + 11.8\text{ev}$	$10^{-8} \text{ cm}^3/\text{s}$	1ms
$\text{Ar}(4s) + \text{N}_2 \rightarrow \text{Ar} + \text{N}_2(\text{C, B, ...})$	$3.6 \times 10^{-11} \text{ cm}^3/\text{s}$	0.01ms
$\text{Ar}(4s) + \text{Ar}(4s) \rightarrow \text{Ar}^+ + \text{Ar} + e$	$10^{-9} \text{ cm}^3/\text{s}$	$1\text{ms} \times (10^{12}/n(4s)[\text{cm}^{-3}])$
$\text{Ar}(4p) + \text{Ar} \rightarrow \text{Ar}(4s) + \text{Ar}$	$\sim 10^{-11} - 10^{-12} \text{ cm}^3/\text{s}$	0.3 - 3mcs
$\text{Ar}(4p) \rightarrow \text{Ar}(4s) + h\nu$	$3.2 \times 10^7 \text{ s}^{-1}$	0.03mcs

The $\text{N}_2(\text{A}^3\Sigma)$ metastable state quenching and building up

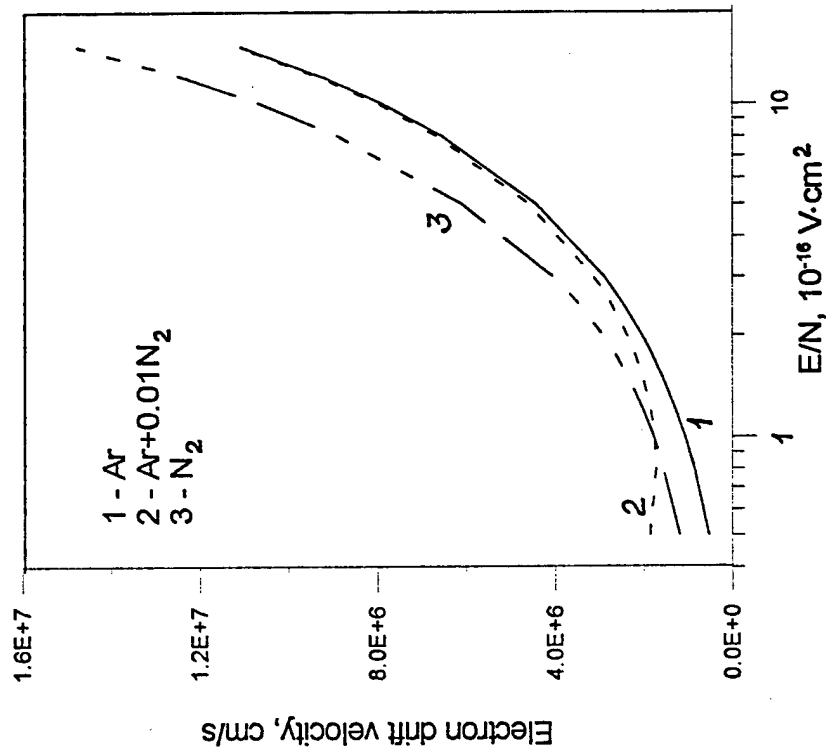
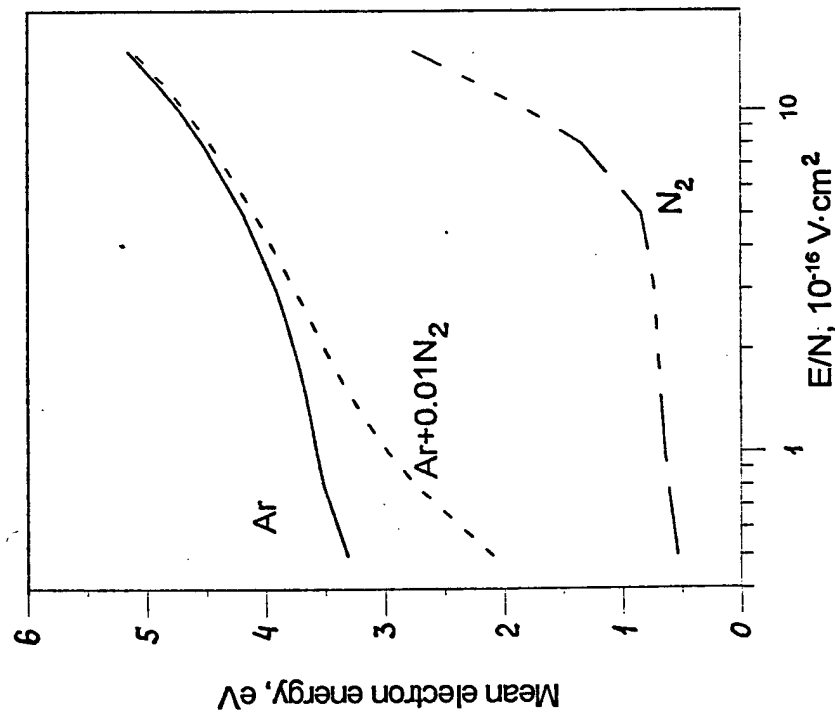
$\text{N}_2(\text{A}^3\Sigma) + \text{Ar} \rightarrow \text{N}_2(\text{X}) + \text{Ar}$	$< 4 \times 10^{-14} \text{ cm}^3/\text{s}$	$> 0.1\text{ms}$
$\text{N}_2(\text{A}^3\Sigma) + \text{N}_2(\text{X}) \rightarrow 2 \text{N}_2(\text{X})$	$< 4.5 \times 10^{-17} \text{ cm}^3/\text{s}$	$> 100\text{ms}$
$\text{N}_2(\text{A}^3\Sigma) + \text{O}_2 \rightarrow \text{N}_2(\text{X}) + \text{O}_2$	$3.6 \times 10^{-12} \text{ cm}^3/\text{s}$	4mcs (for air composition)
$\text{N}_2(\text{A}^3\Sigma) + \text{N}_2(\text{X}, \nu) \rightarrow \text{N}_2(\text{B}^3\Pi) + \text{N}_2(\text{X})$	$\sim 10^{-10} \text{ cm}^3/\text{s}$	
$\text{N}_2(\text{A}^3\Sigma) + \text{N}_2(\text{A}^3\Sigma) \rightarrow \text{N}_2(\text{B, C, ...}) + \text{N}_2(\text{X})$	$10^{-9} \text{ cm}^3/\text{s}$	$1\text{ms} \times (10^{12}/n(\text{A})[\text{cm}^{-3}])$
$\text{N}_2(\text{B}^3\Pi) + \text{N}_2(\text{X}) \rightarrow \text{N}_2(\text{A}^3\Sigma) + \text{N}_2(\text{X})$	$2 \times 10^{-11} \text{ cm}^3/\text{s}$	0.15mcs
$\text{N}_2(\text{B}^3\Pi) \rightarrow \text{N}_2(\text{A}^3\Sigma) + h\nu$	$1.5 \times 10^5 \text{ s}^{-1}$	6.5mcs
$\text{N}_2(\text{C}^3\Pi) \rightarrow \text{N}_2(\text{A, B}) + h\nu$	$2.7 \times 10^7 \text{ s}^{-1}$	0.037mcs

The discharge fractional power input into different excited states for Ar, N₂ and Ar-N₂ mixture

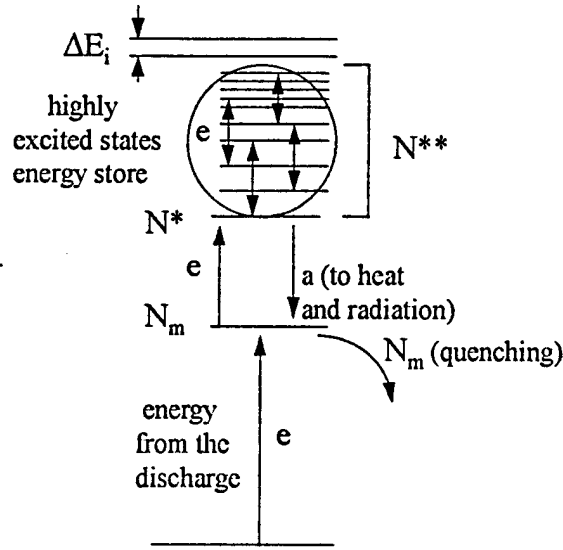
E-is electric field strength, N - is gas number density



The mean electron energy (electron temperature) and electron drift velocity versus E/N value for Ar, Ar+0.01N₂ and N₂ discharges



The kinetic model of energy storing in highly excited states



The system of balance equations for excited states

$$\frac{\partial N_m}{\partial t} = \frac{W\eta}{E_m} - N_m \left(k_p N_m + \frac{1}{\tau_q} \right) - k_e n_e N_m + N^* (k_q N + A_R \theta)$$

$$\frac{\partial N^*}{\partial t} = k_e n_e N_m - N^* (k_q N + A_R \theta)$$

$$N^{**} = \sum_{n=n^*}^{n_f} N^* \frac{g_n}{g_{n^*}} \exp\left(-\frac{E_n - E_{n^*}}{T_e}\right), \quad \text{for } n > n^* \quad k_e n_e \gg k_q N \frac{\Delta E_{n,n+1}}{T_e},$$

$$\Delta E_{n,n+1} \approx \frac{2Ry}{n^3}, \quad n^* \approx \sqrt[3]{\frac{2Ry}{T_e} \frac{k_q N}{k_e N_e}} \approx 4-5, \quad E_i - E^* \approx 0.5-1 \text{ eV}$$

$Ry = 13.6 \text{ eV}$ is the Rydberg constant

$W = jE$ - is the discharge specific power;

$\eta \sim 1$ - is the discharge fractional power input into excitation;

E_m, E_n - are the energies of the different states excitation from the ground state;

k_p - is the metastable atom Penning process rate constant;

τ_q - is the metastable state quenching time in other processes;

k_e - is the electron excitation rate constant from metastable to N^* states;

k_q - is the gas quenching rate constant for N^* states;

A_R - is the radiative decay rate for N^* states;

θ - is the probability of radiation trapping;

ΔE_i - is the decrease of ionization potential due to excited atom electron - ion interaction;

For the tube radius R

$$\theta = \frac{1}{3\sqrt{\pi\sigma_{abs}N_m R}}$$

For Ar(4p) \rightarrow Ar(4s) transitions $\theta \approx 3 \times 10^{-2} (10^{12}/N_m)^{0.5}$ followed by

$$A_R \theta \ll k_q N$$

The steady state values of N_m and N^* :

$$N_m \approx \sqrt{\frac{W\eta}{k_p E_m}} \approx 2.5 \times 10^{13} \sqrt{W[W/cm^3]}, cm^{-3}$$

$$N^* \approx N_m \frac{k_e n_e}{k_q N} \approx 3.5 \times 10^{12} \frac{\sqrt{W[W/cm^3]}}{p[Torr]}, cm^{-3}$$

The equilibrium highly excited hydrogen-like states population

$$n_f \approx \sqrt{\frac{Ry}{\Delta E_i}} \approx \sqrt{\frac{Ry}{e^2 N_i^{\frac{1}{3}}}} - \text{the upper limit of principle quantum number for hydrogen-like states;}$$

$$n_f \approx 100 \text{ for } N_i \approx 10^{11} cm^{-3}$$

$$N^{**} \approx N^* \frac{2n_f^3}{3g^*} \exp\left(-\frac{E_i - E^*}{T_e}\right) \sim 10^4 N^*$$

$g^* \sim 30$ is the degeneracy of N^* state

The energy stored in highly excited states

$$\varepsilon^{**} \approx (E^* - E_m) \frac{n_f^3}{g^*} \frac{k_e N_e}{k_q N} \sqrt{\frac{W\eta}{E_m k_p}} \exp\left(-\frac{E_i - E^*}{T_e}\right)$$

$$\varepsilon^{**} \approx 10^{17} \frac{\sqrt{W[W / \text{cm}^3]}}{p[\text{Torr}]}, \frac{\text{eV}}{\text{cm}^3},$$

$$\frac{\varepsilon^{**}}{c_p N T} \approx 1$$

The energy released to heat behind the shock wave

$$\Delta\varepsilon \approx \varepsilon^{**} \left(1 - \frac{N_0 N_{e1}}{N_1 N_{e0}}\right)$$

0 and 1 indexes correspond to the gas and plasma parameters before and behind the shock

The relaxation length behind the SW front

$$\xi_r \approx D \frac{N_0}{N_1} \frac{1}{k_p N_m} \approx 4 \times 10^{-5} \frac{N_0}{N_1 \sqrt{W[W / \text{cm}^3]}} D[\text{cm} / \text{s}], \quad \text{cm}$$

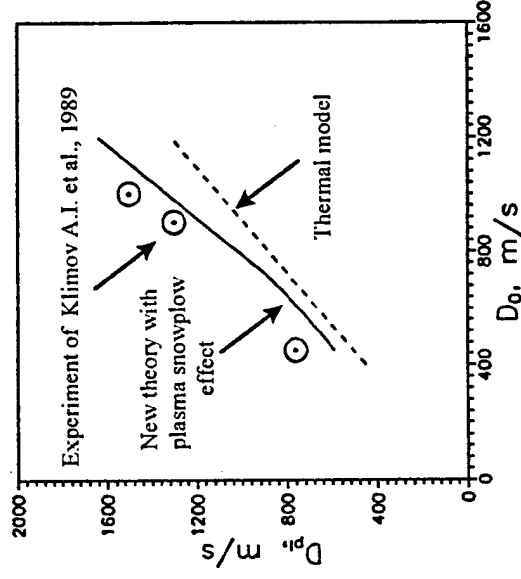
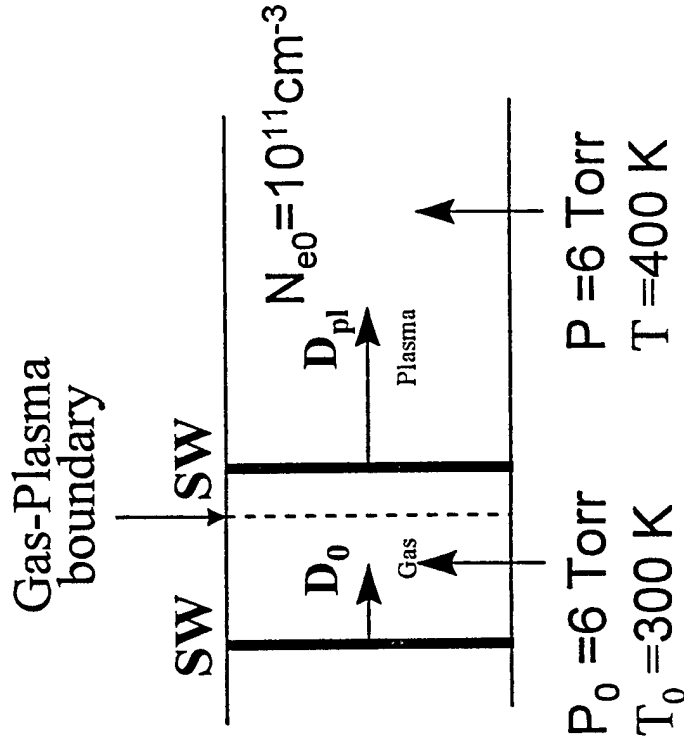
Inclusion of Plasma Effects Dramatically Improves Agreement of Theory with Experiment for 1-D Shock Penetrating Into a Plasma

Physical System

$$1.3 < M < 3.5, \quad M = D_0/a_0,$$

a_0 = sound velocity

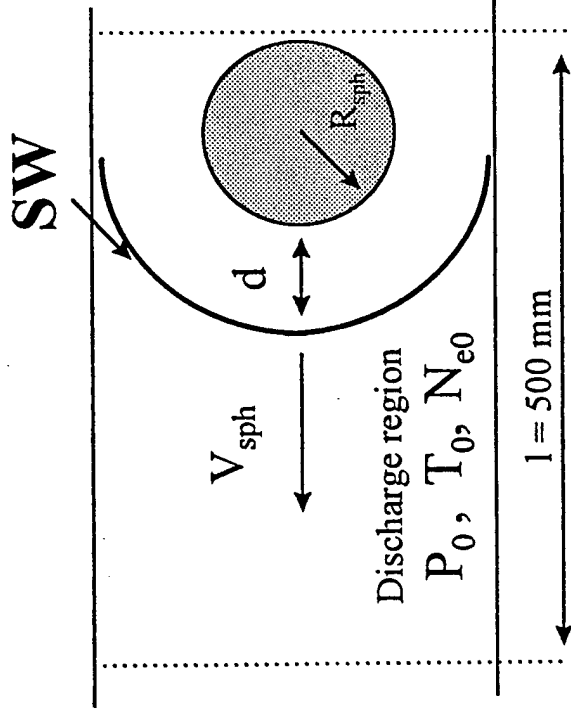
Dependence of shock speed in plasma D_{pl} versus the initial shock speed D_0 in undisturbed gas.



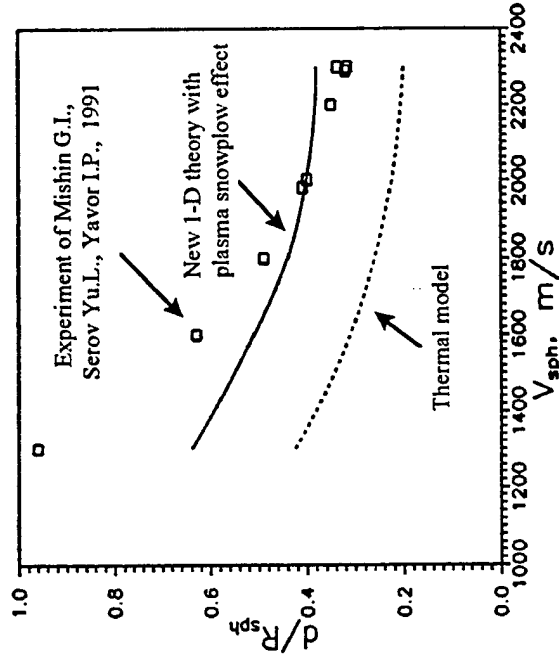
Inclusion of Plasma Effects Dramatically Improves Agreement of Theory with Experiment for Hypersonic Sphere Entering a Plasma

Physical System

$P_0=45$ Torr, $T_0=1350$ K, $N_{e0}=10^{11}\text{cm}^{-3}$,
 $1.7<M<3.2$, $M=V_{\text{sph}}/a_0$, $R_{\text{sph}}=20$ mm



Dependence of relative shock
 standoff distance d/R_{sph} from
 the sphere versus the speed
 of the sphere V_{sph} .



Conclusions

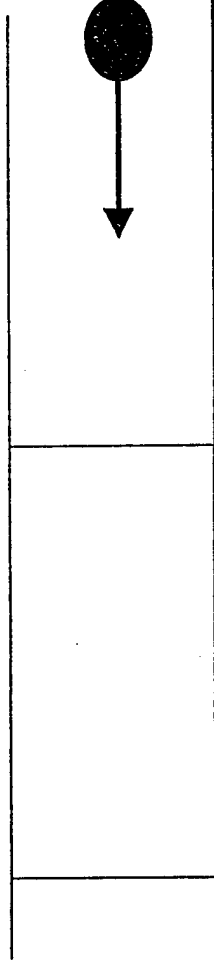
- The mechanism of shock wave (SW) acceleration and attenuation due to interaction with a weakly ionized plasma really exists
- Preliminary calculations of 1-D SW speed in plasma are in a good agreement with experimental results when the highly excited states energy release behind the SW front is taken into account
- SW acceleration is accompanied by decrease of density and velocity jump with a small increase of static pressure jump through the SW front
- The foregoing results in a decrease of dynamic pressure jump through the SW front
- The creation of a discharge plasma IN FRONT OF the shock wave courses the SW attenuation and drag reduction for supersonic and hypersonic vehicles
- More detailed kinetic analysis is necessary to obtain more precise results

Anomalous Behavior of Shocks in Weakly Ionized Gases - Theory & Modeling

Vish V. Subramaniam
Department of Mechanical Engineering
and Chemical Physics
The Ohio State University
Columbus, Ohio 43210

- Anomalous effects seen in two different types of experiments:

(1) Ballistic range

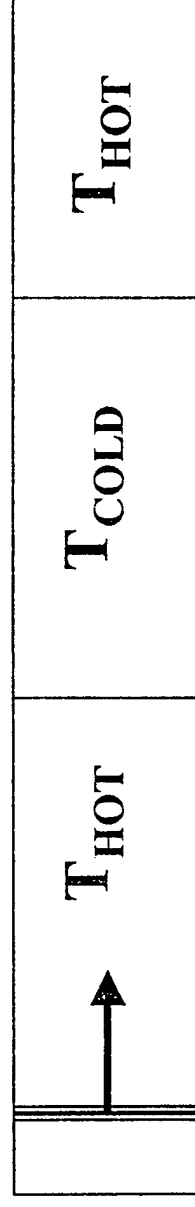
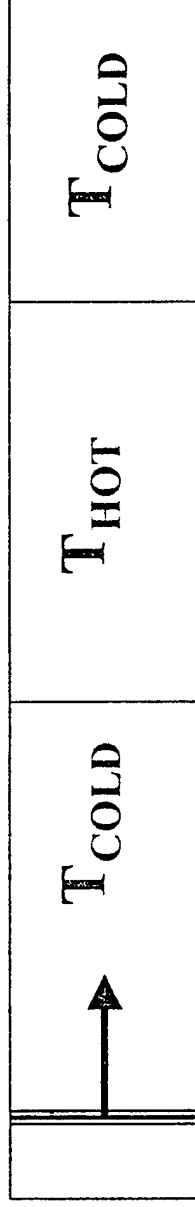


(2) Spark-generated shock launched into a glow discharge (WPAFB)

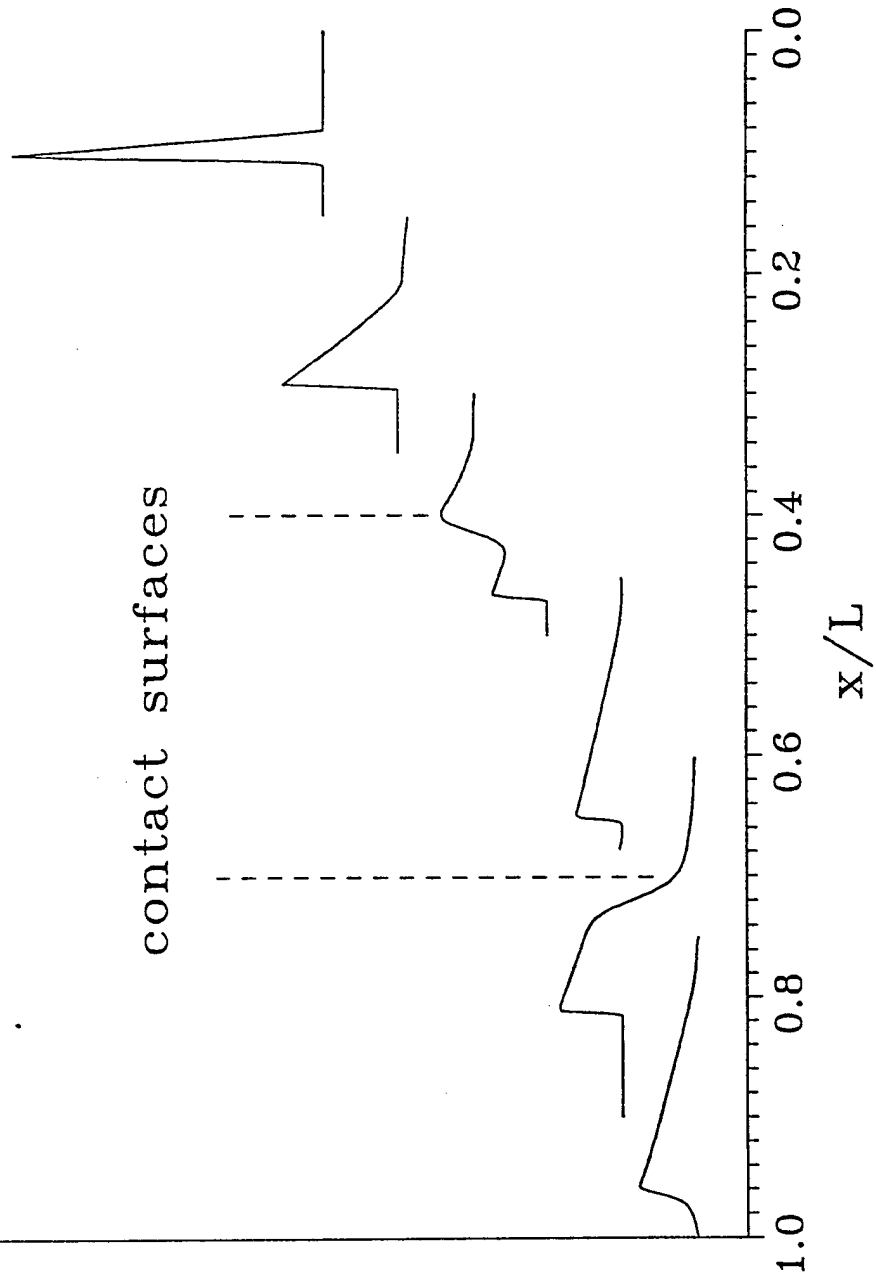


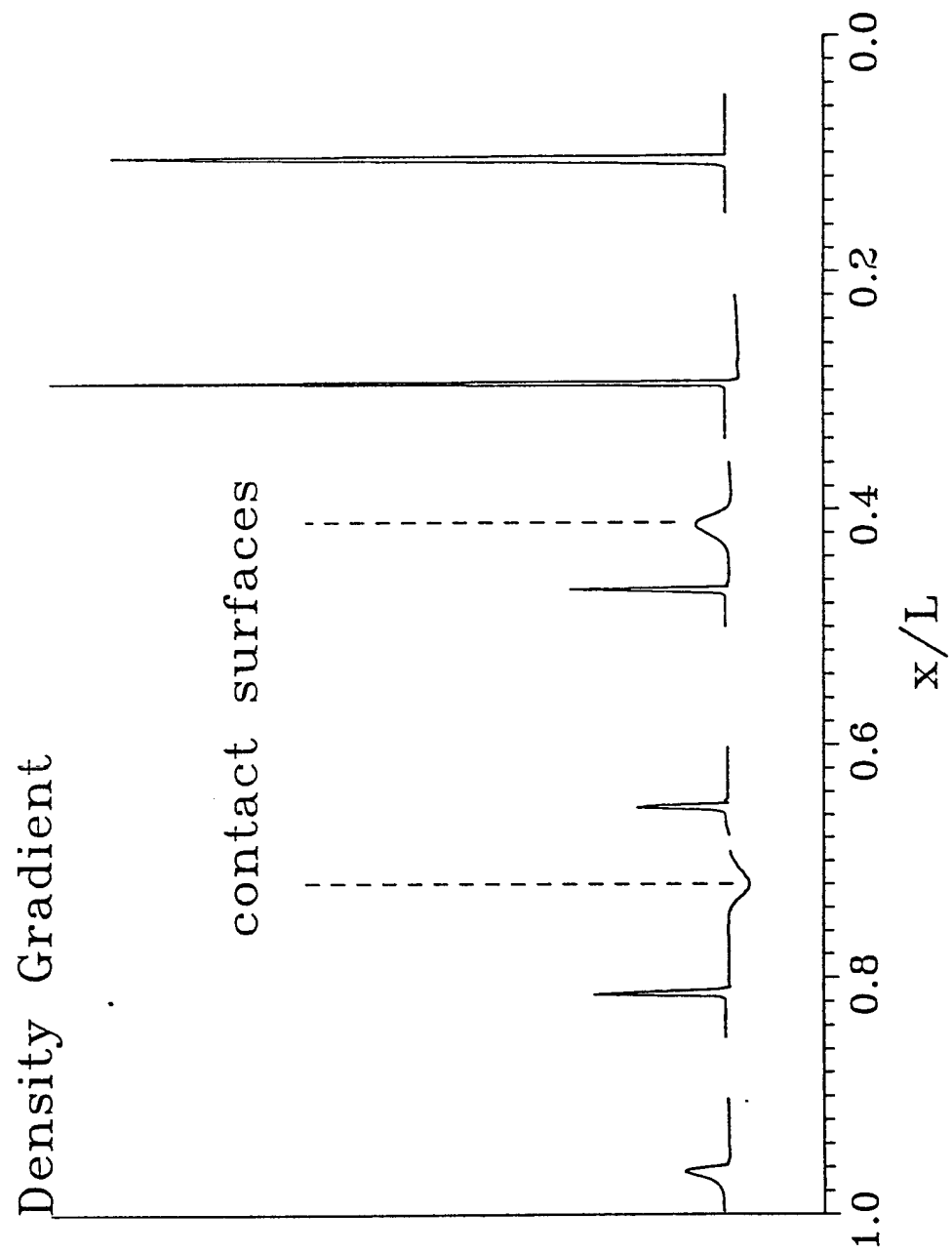


Effects of purely axial thermal gradients

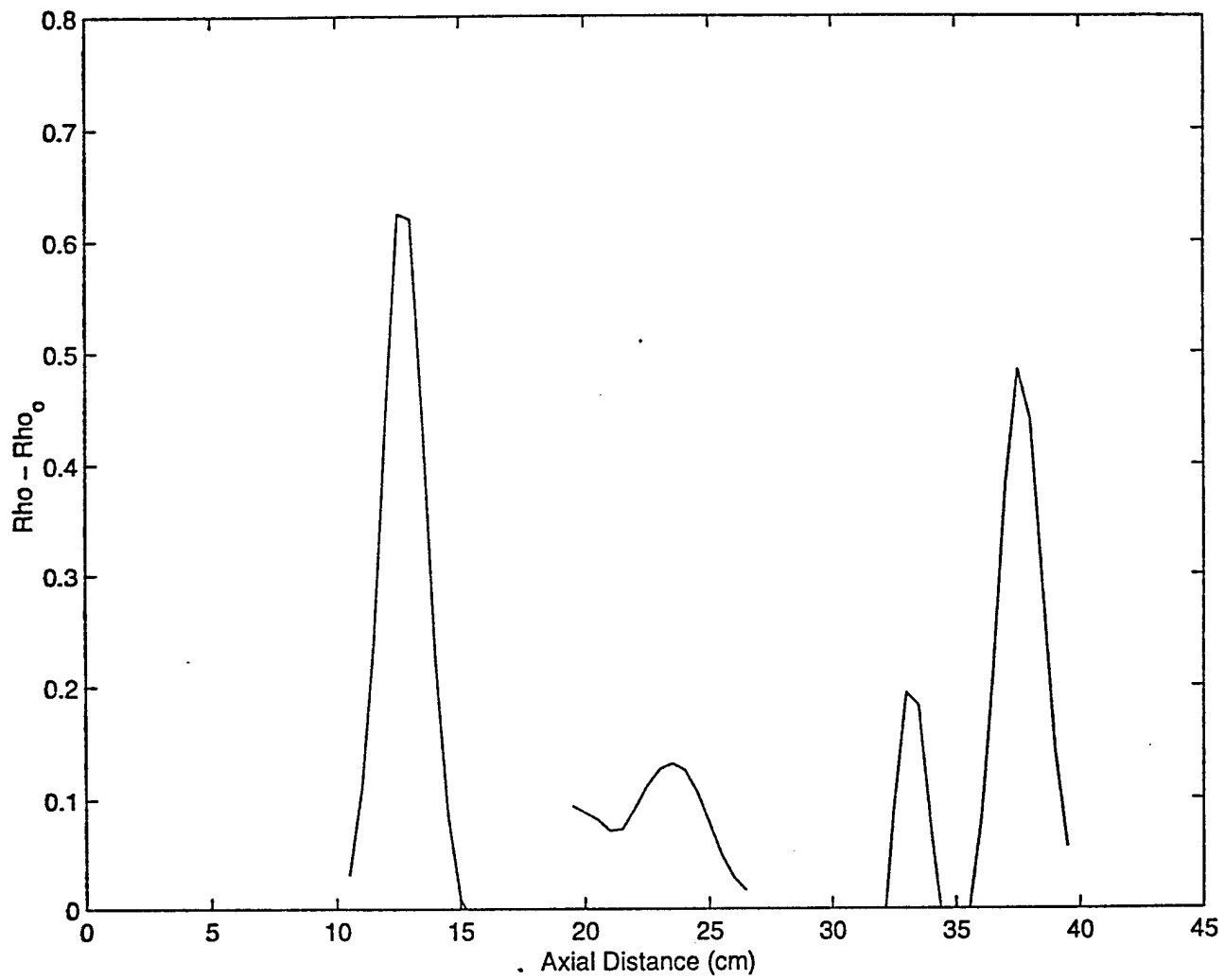


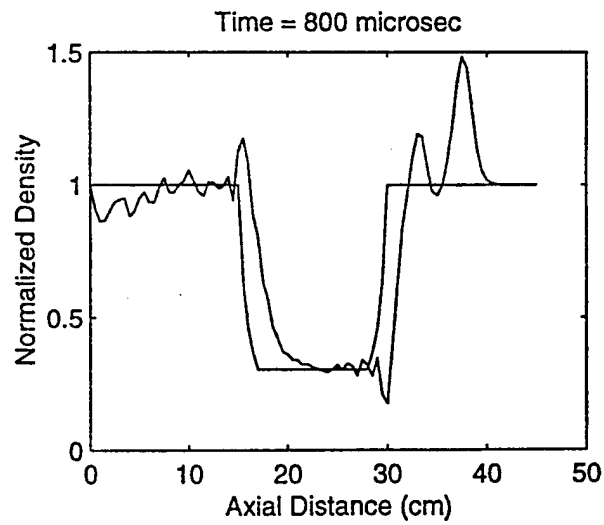
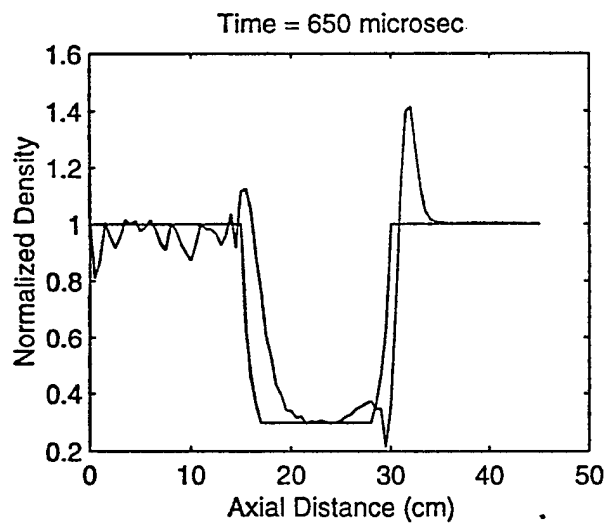
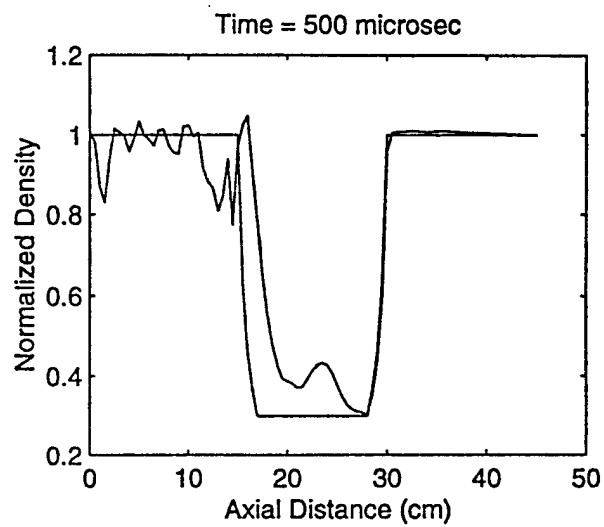
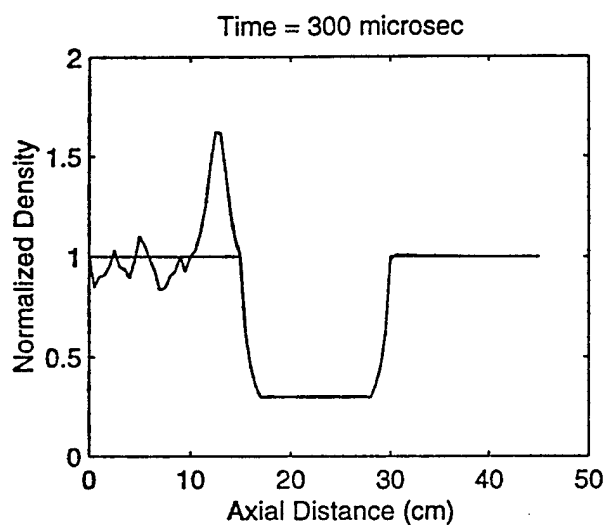
Density Profiles

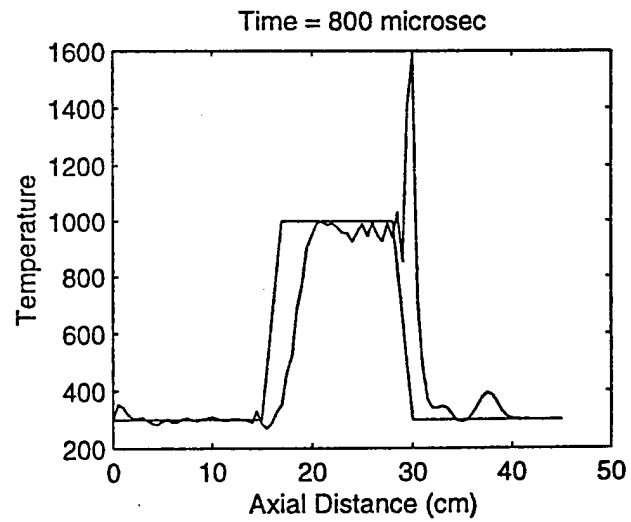
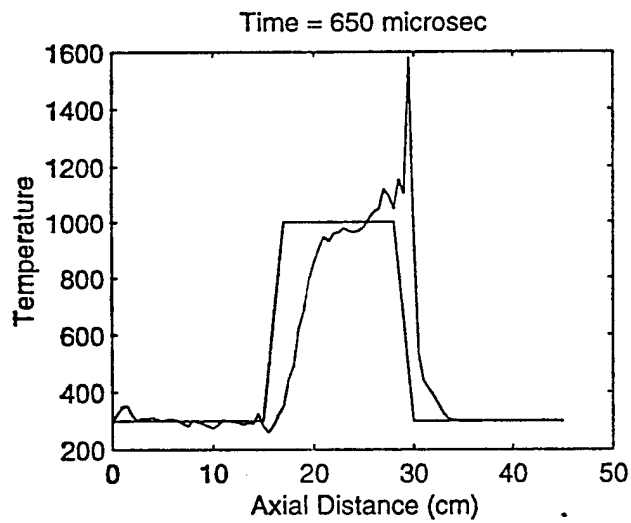
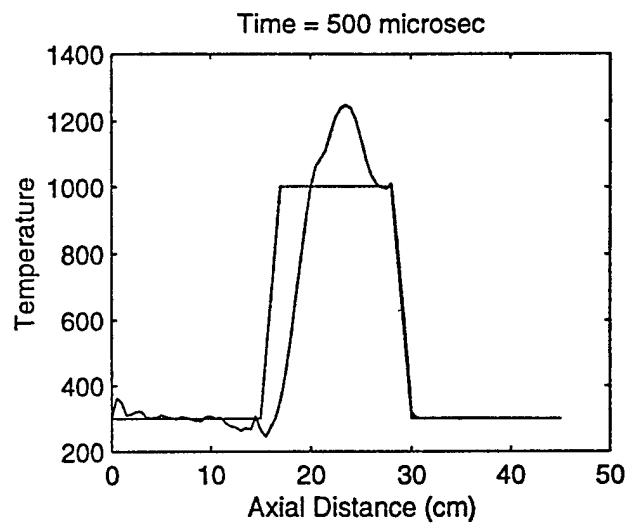
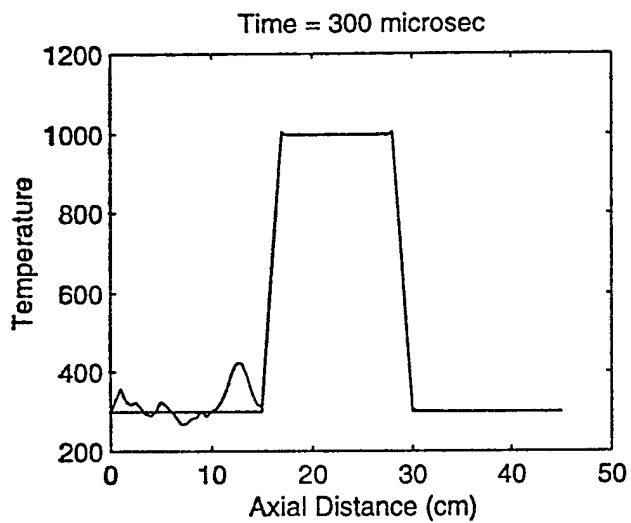


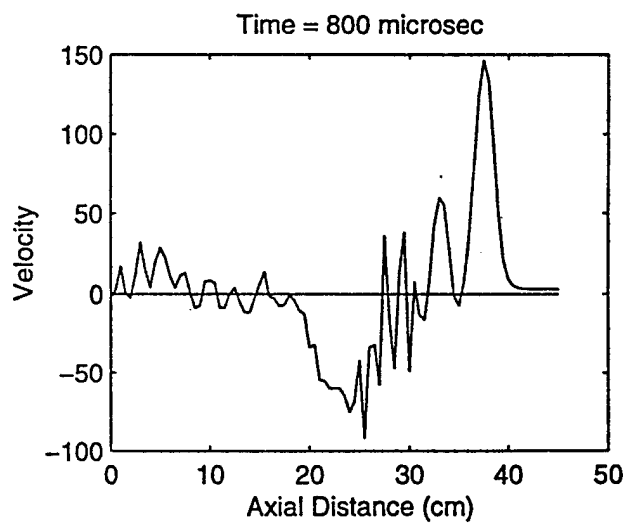
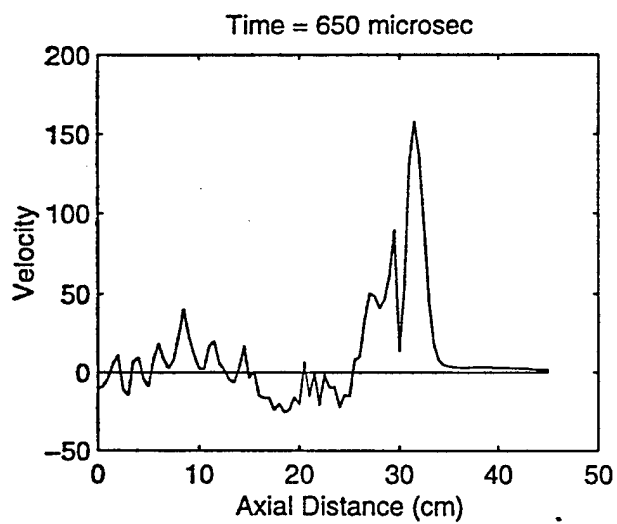
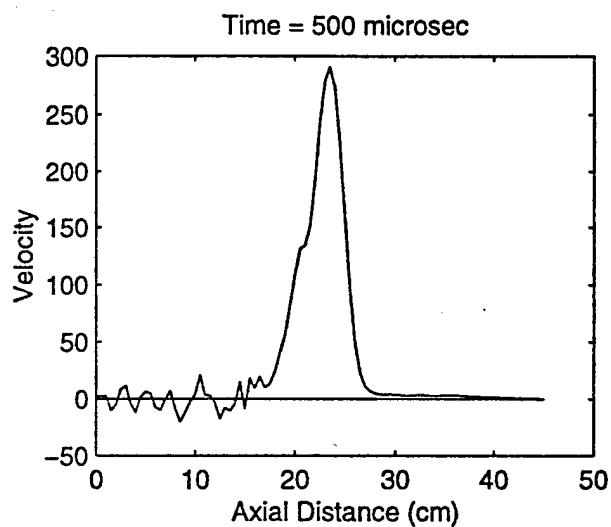
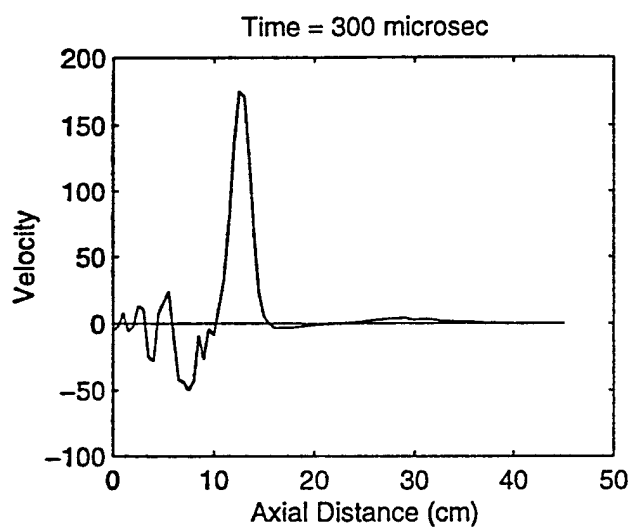


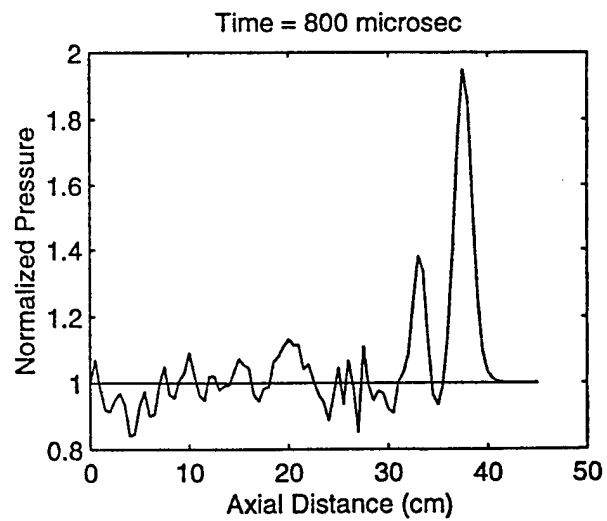
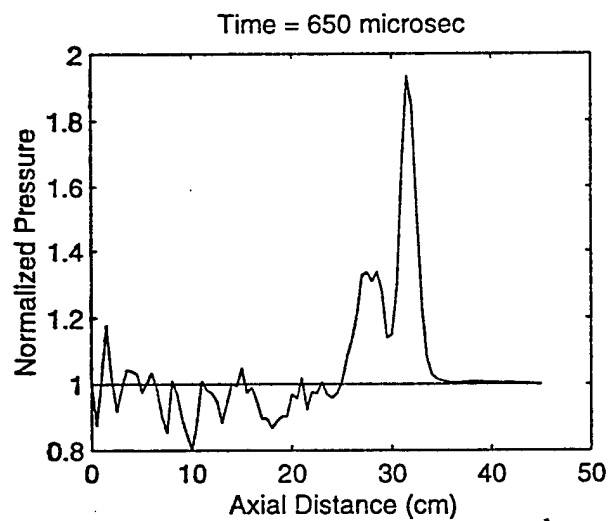
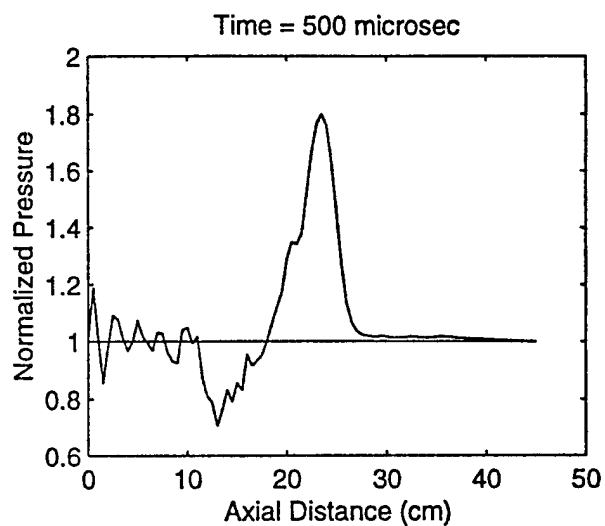
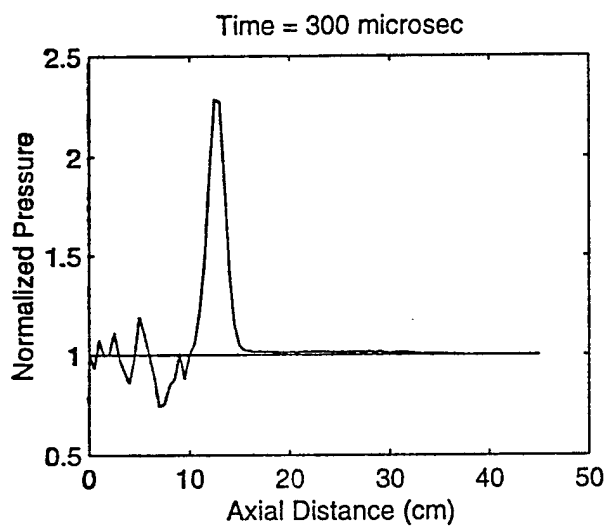
3.60/1.50' 73



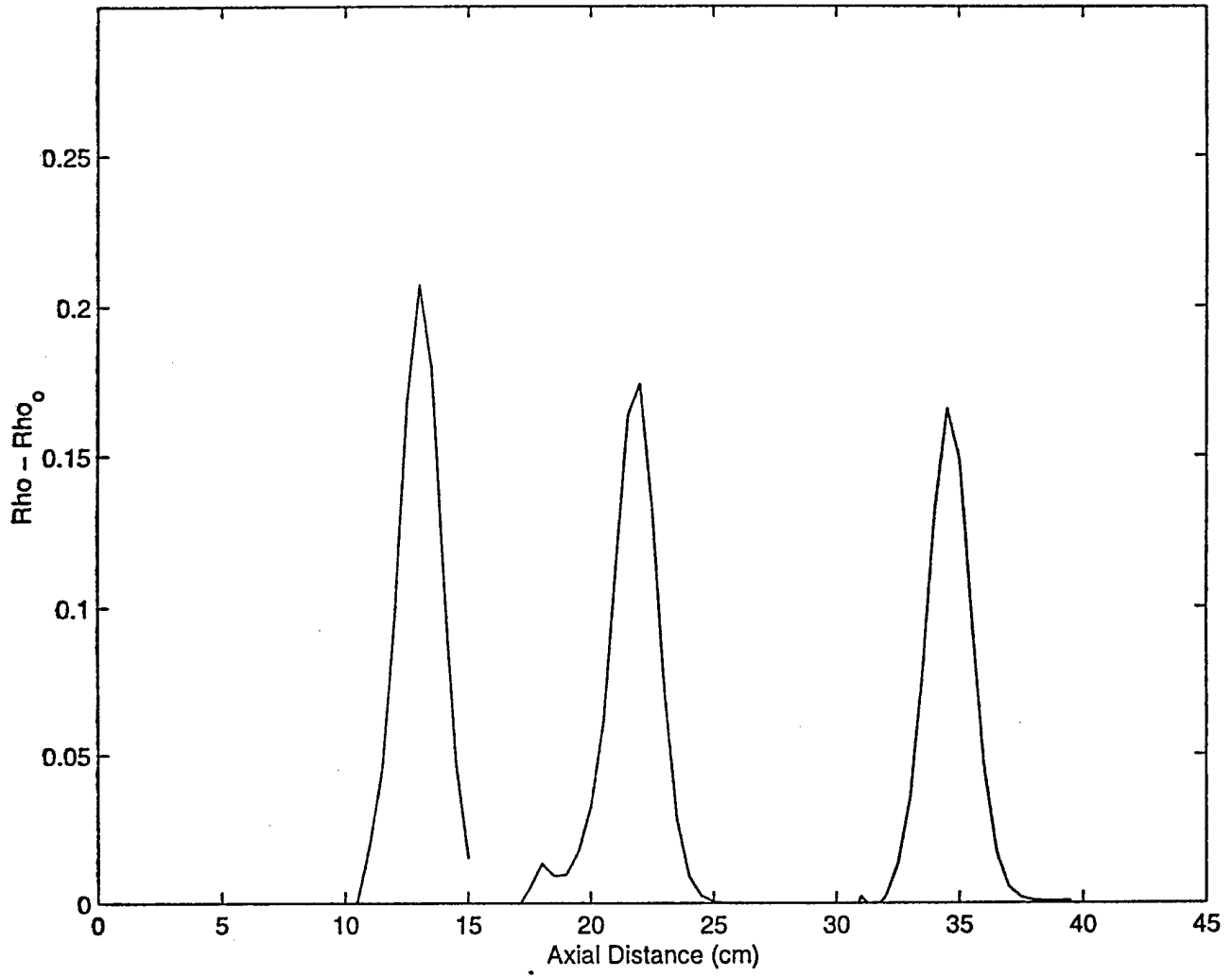




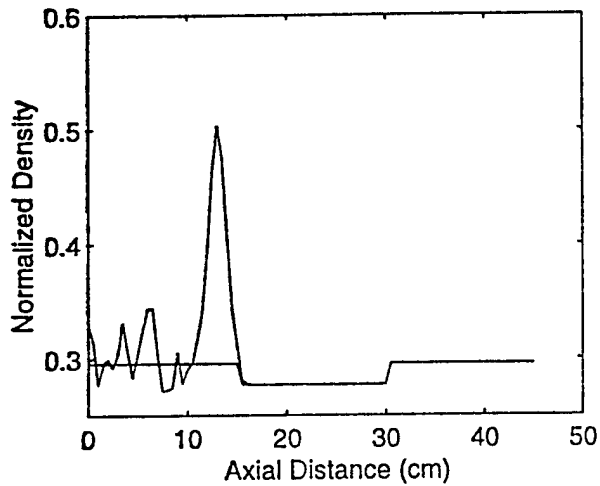




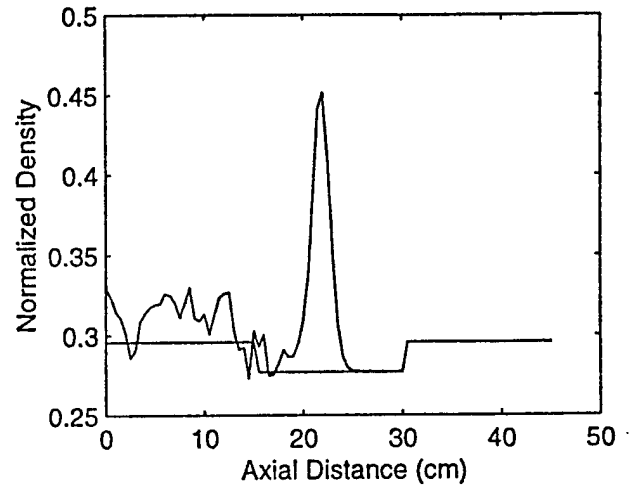
350/3. .80



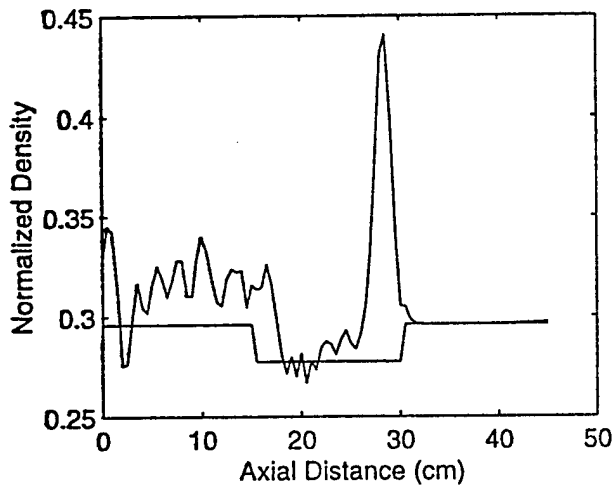
Time = 300 microsec



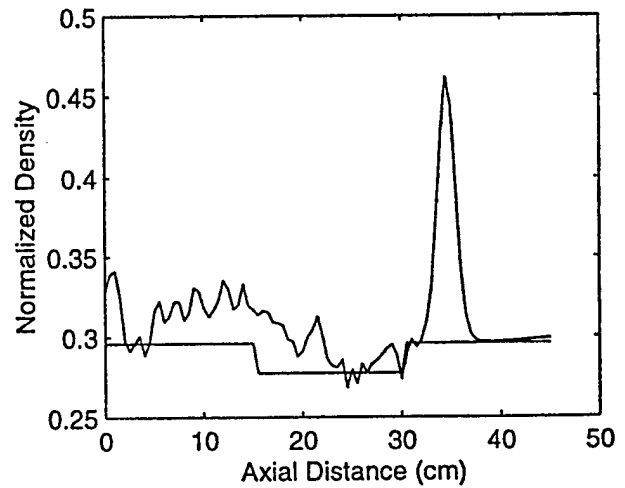
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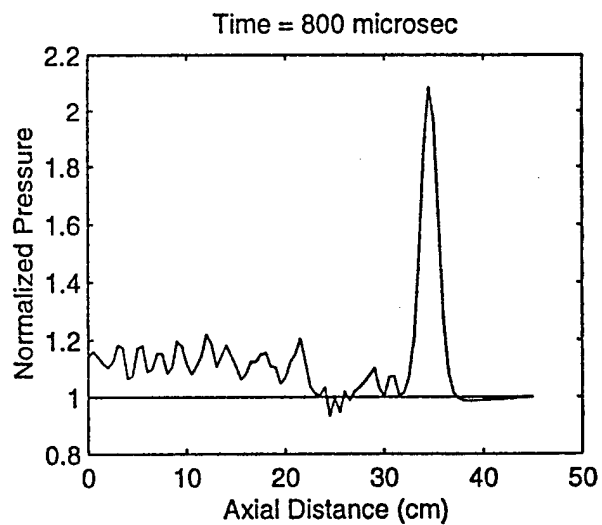
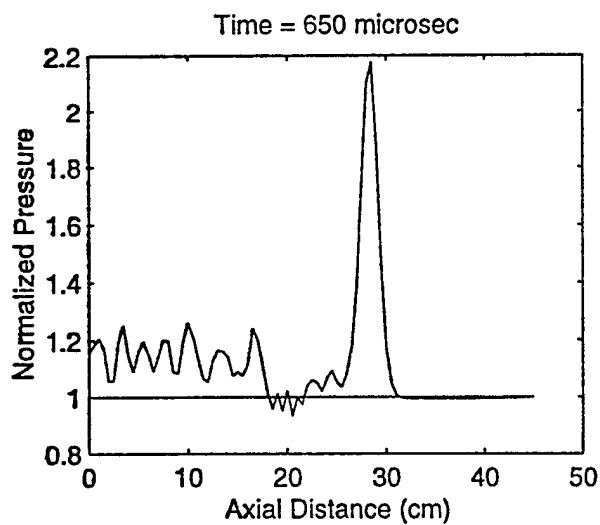
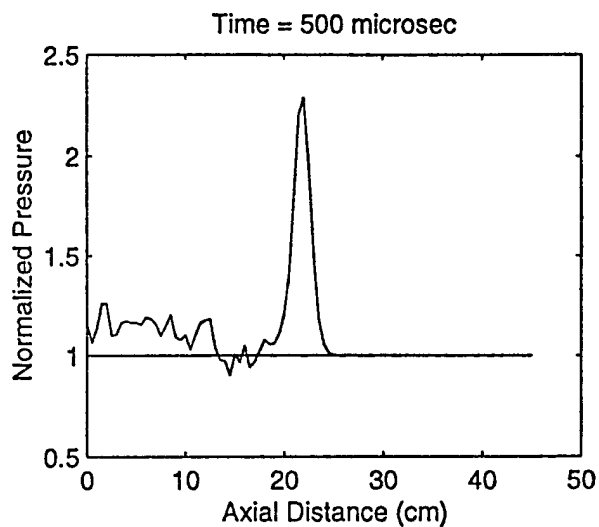
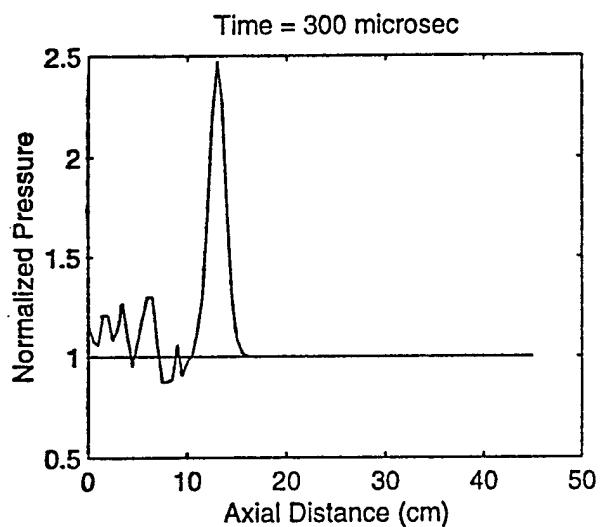


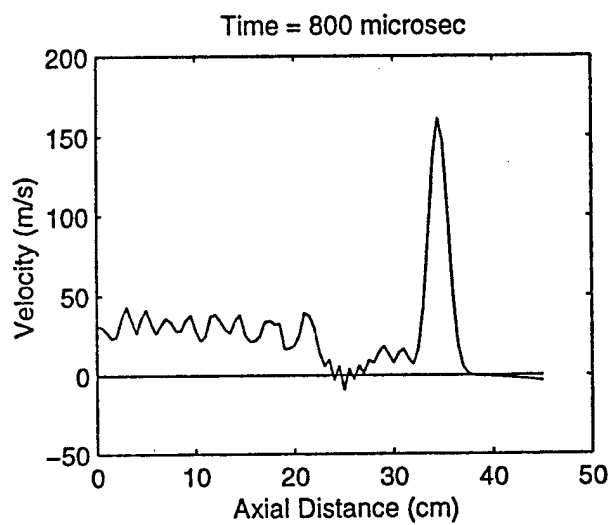
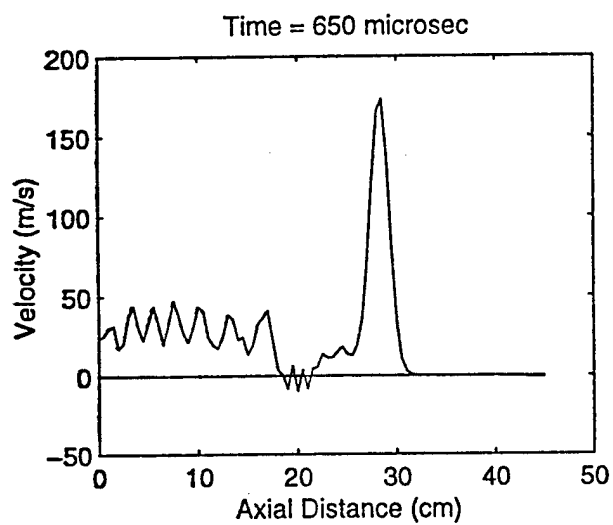
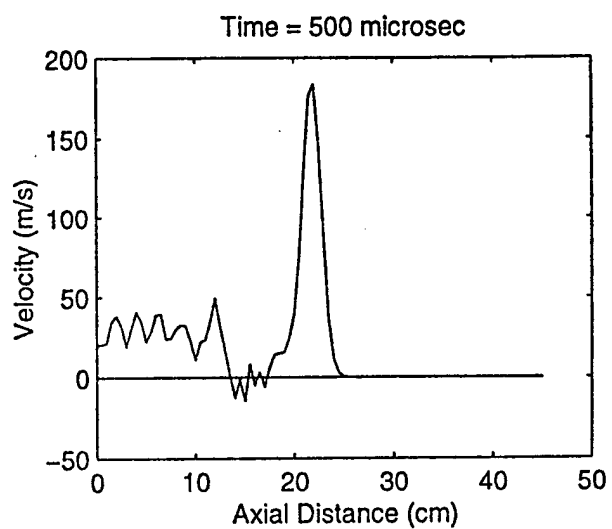
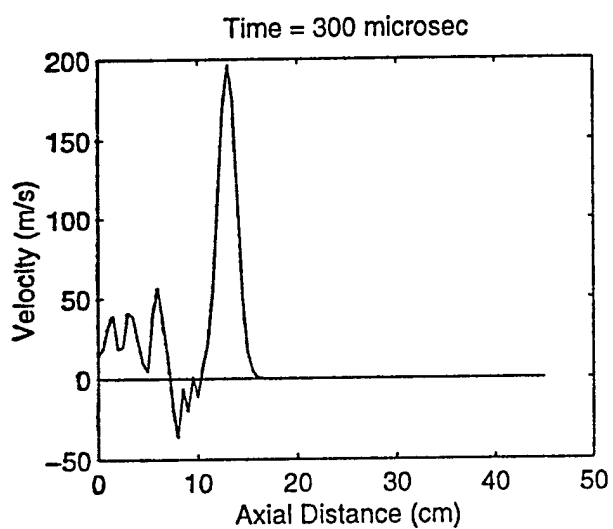
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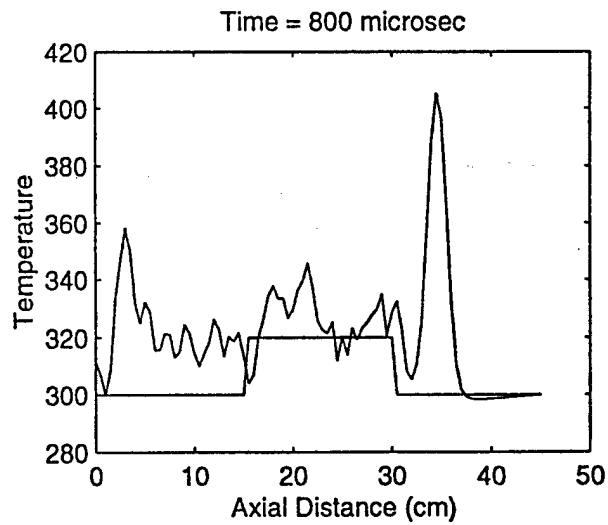
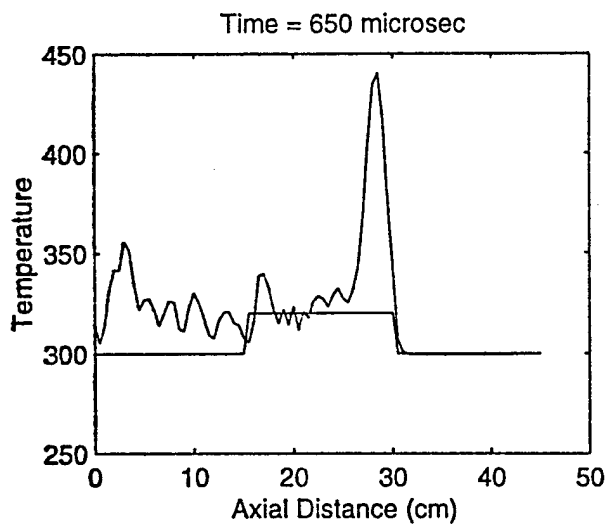
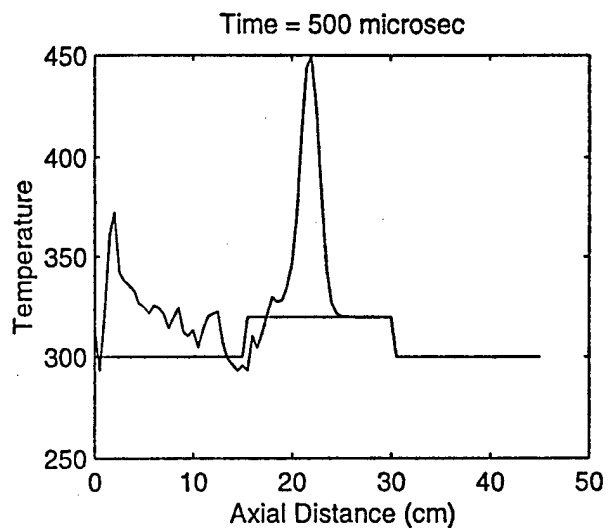
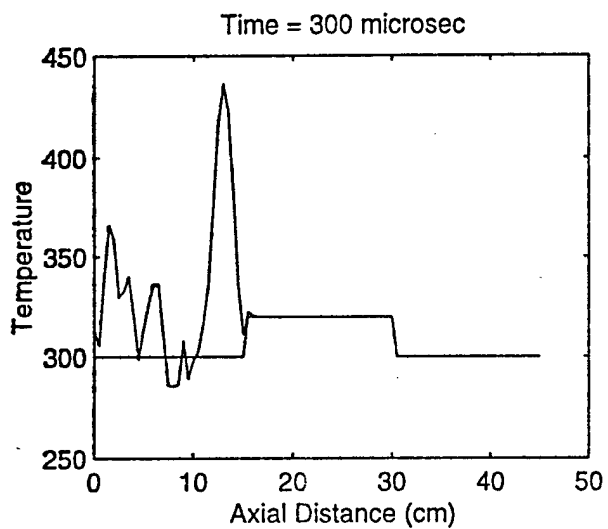


Time = 800 microsec

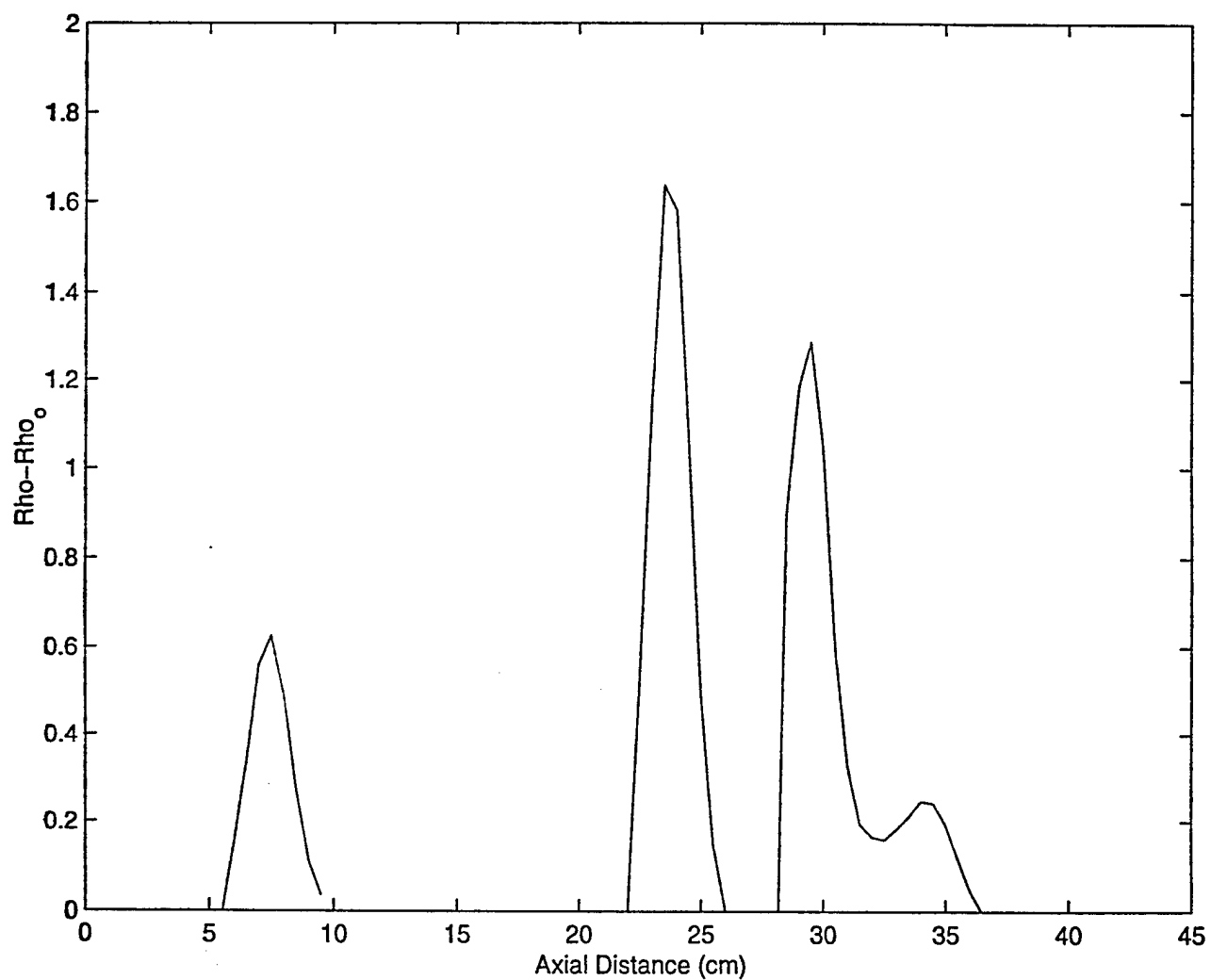






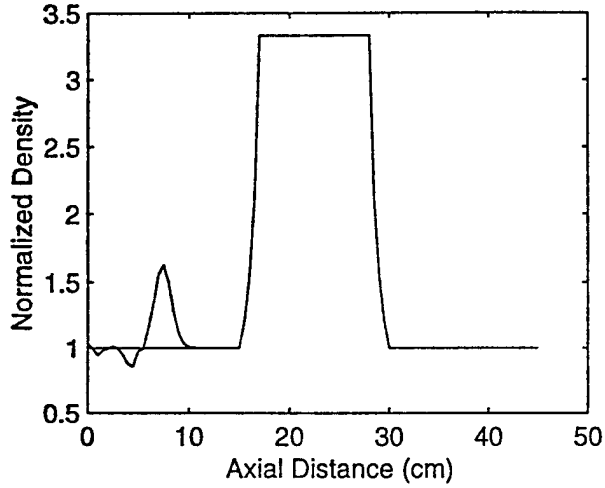


150/350/1000

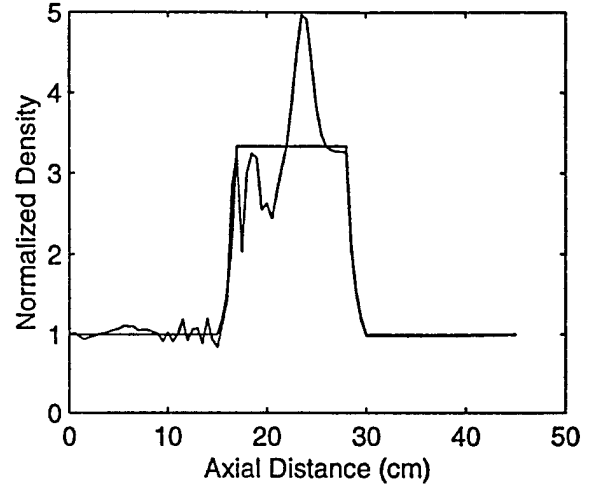


150/300/1000

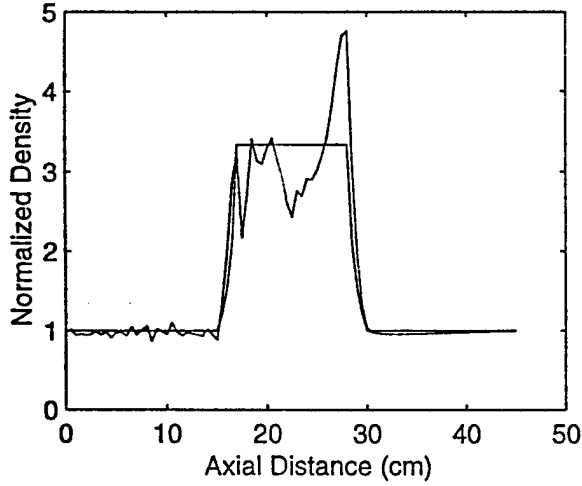
Time = 100 Microseconds



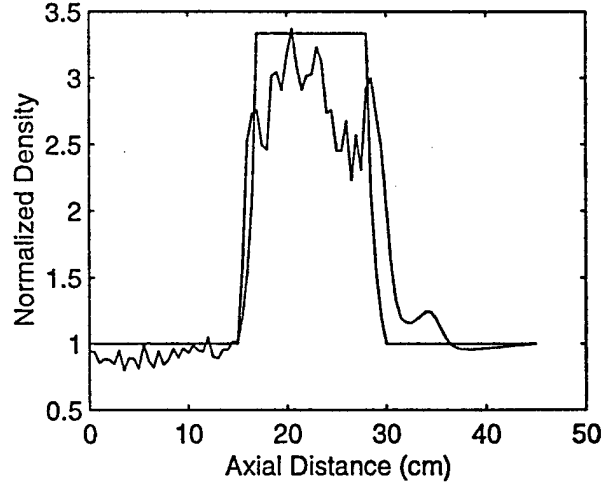
Time = 400 Microseconds

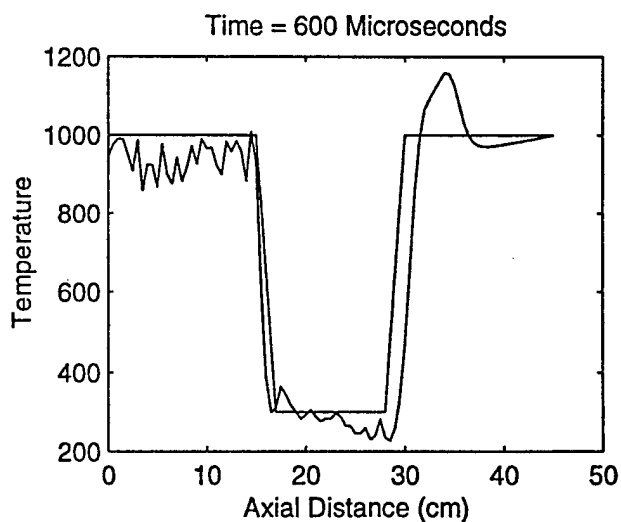
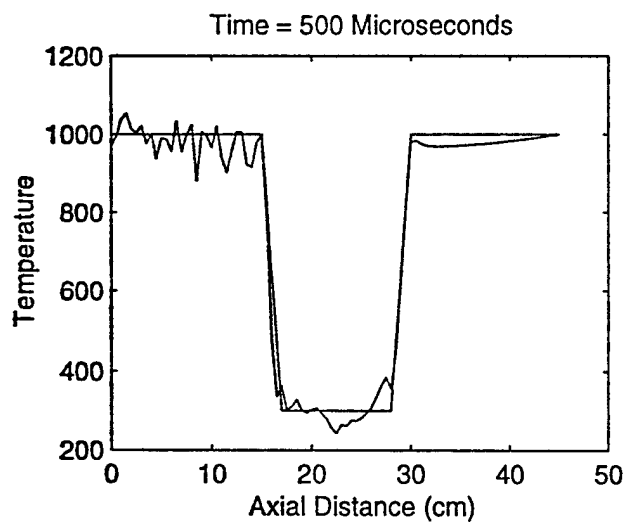
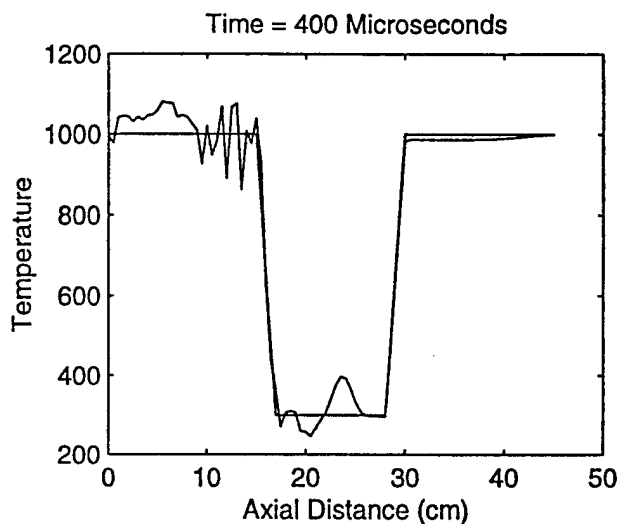
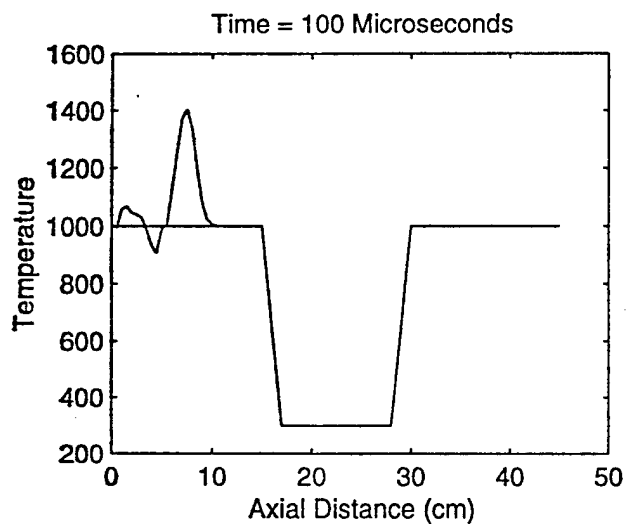


Time = 500 Microseconds



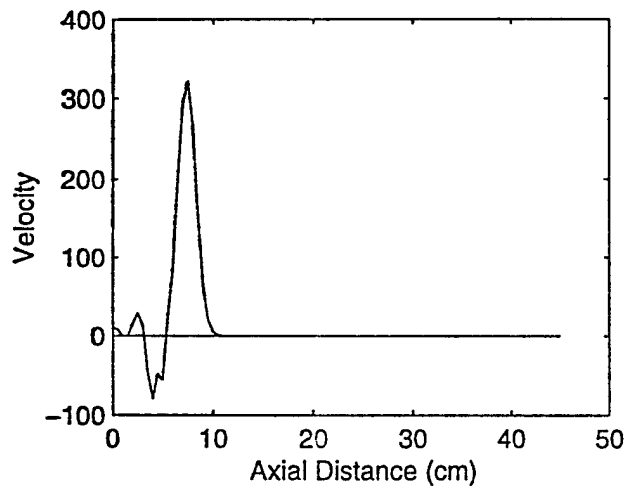
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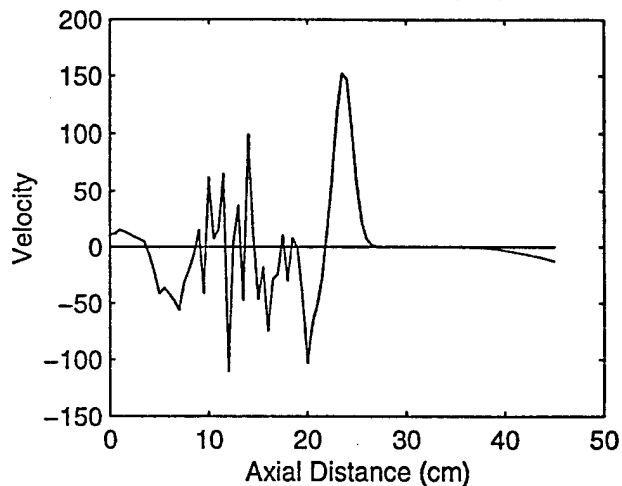


150, 350/1500

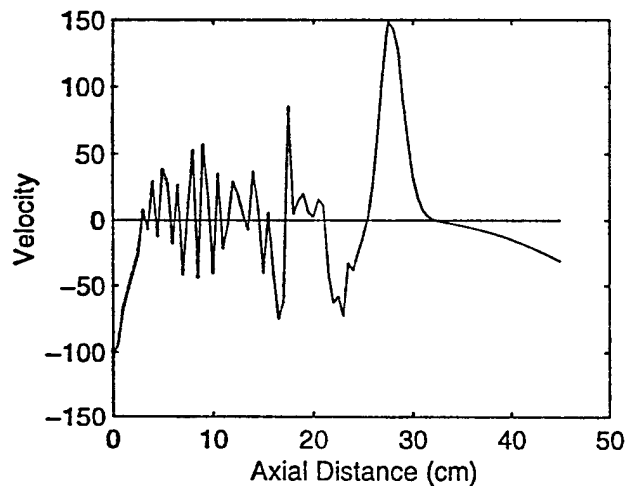
Time = 100 Microseconds



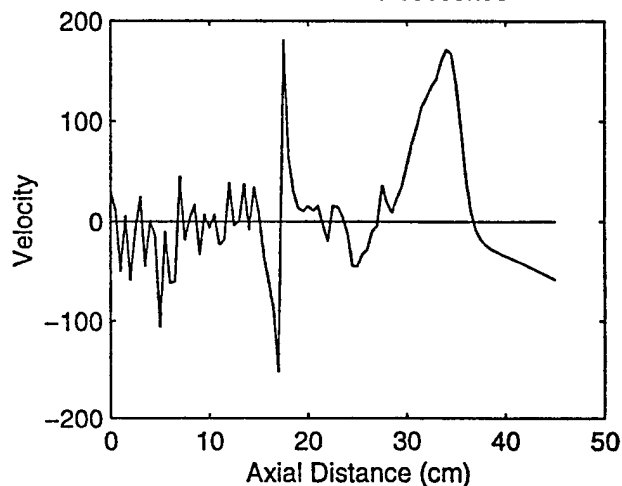
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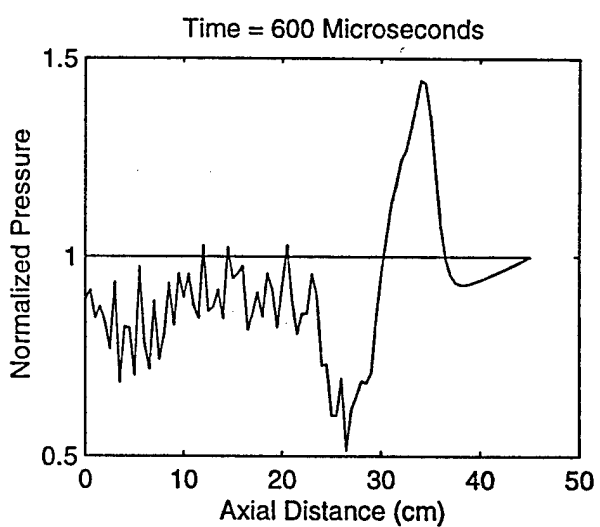
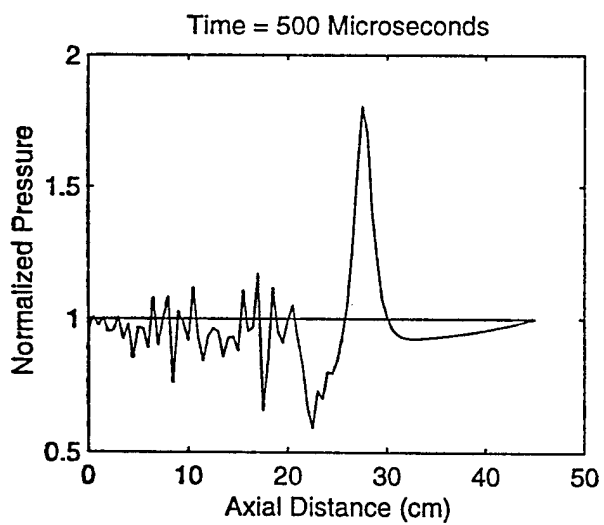
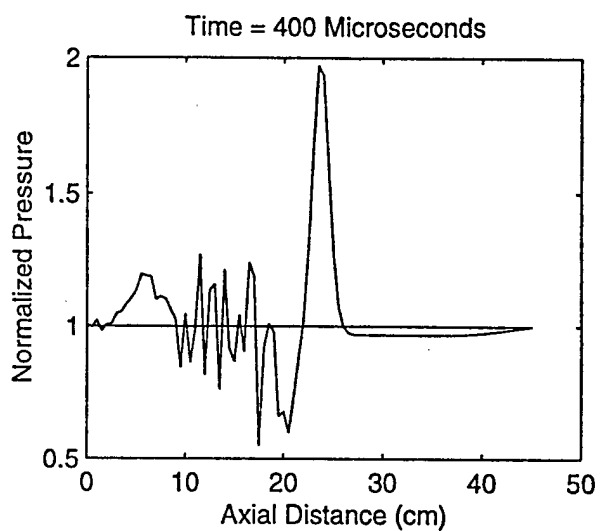
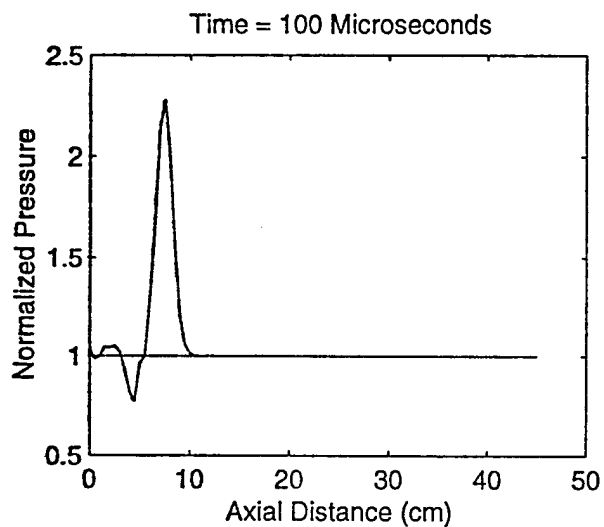


Time = 500 Microseconds



Time = 600 Microseconds

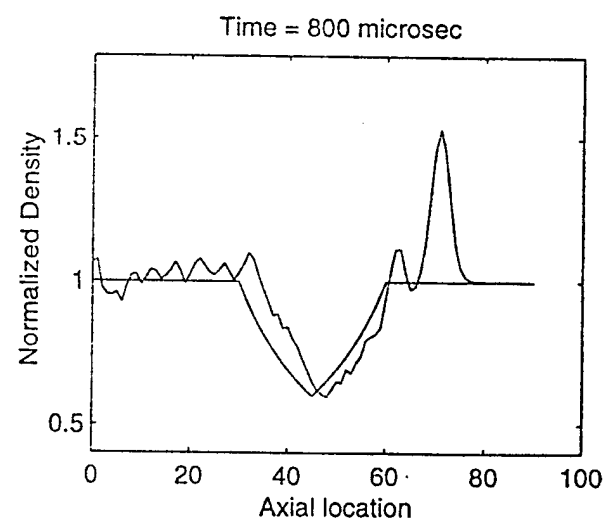
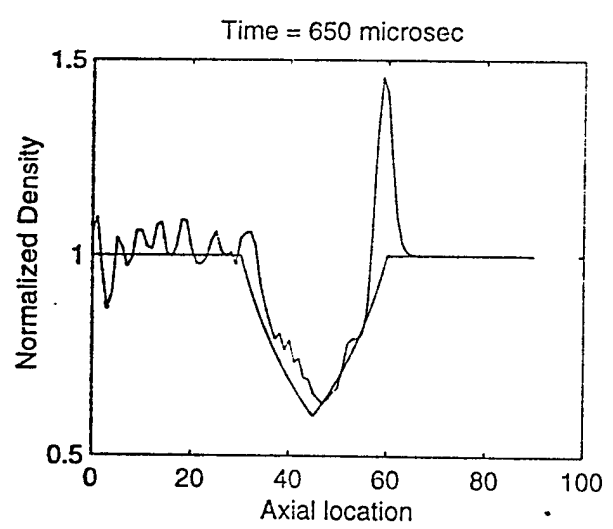
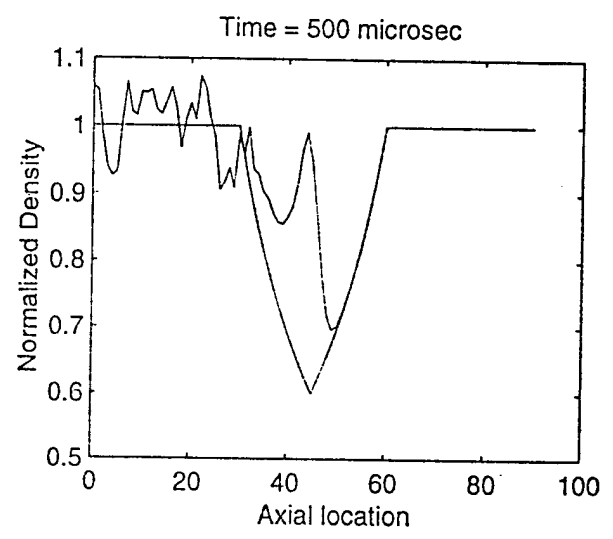
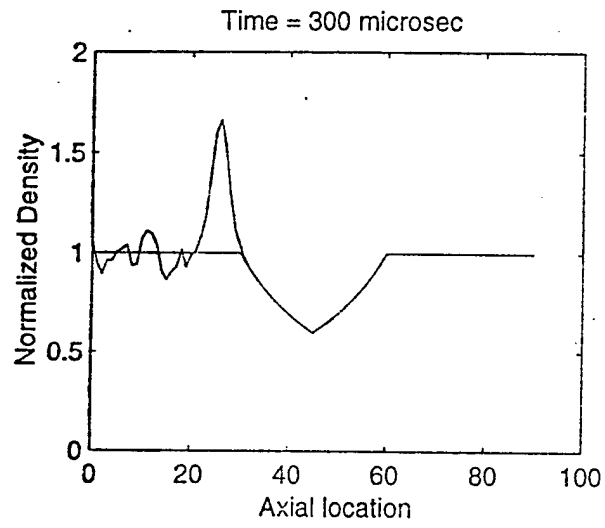




8/98

- 1) No radial ^{temp} grad
- 2) Triangular axial ^{temp} grad
- 3) NO plasma.

CASE III



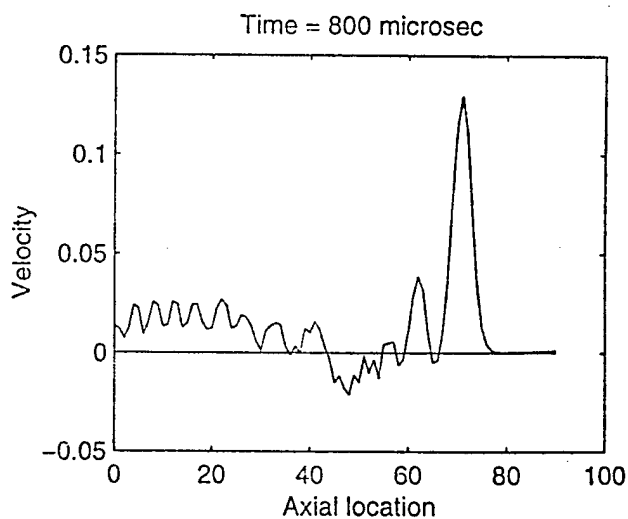
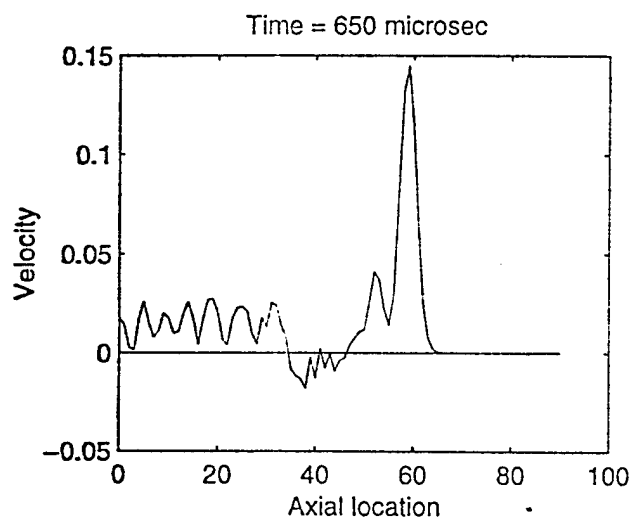
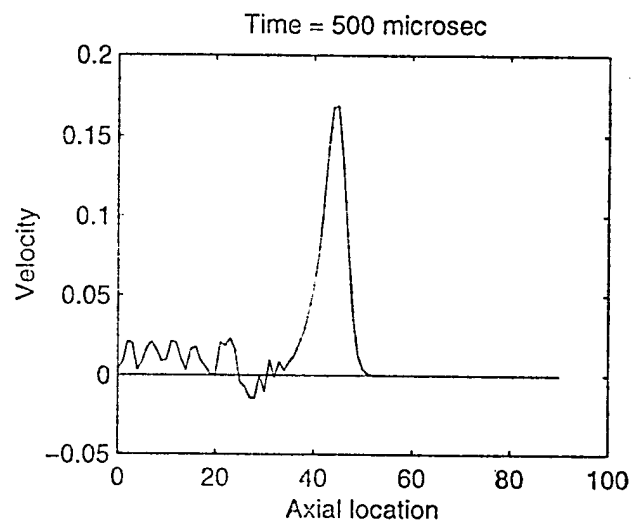
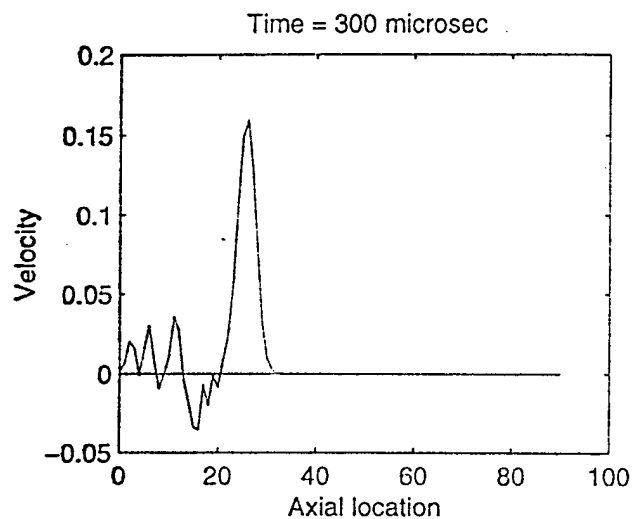
1/8/98

1) No radial len
gro

2) Triangular
axial lenp gr

3) No plasma.

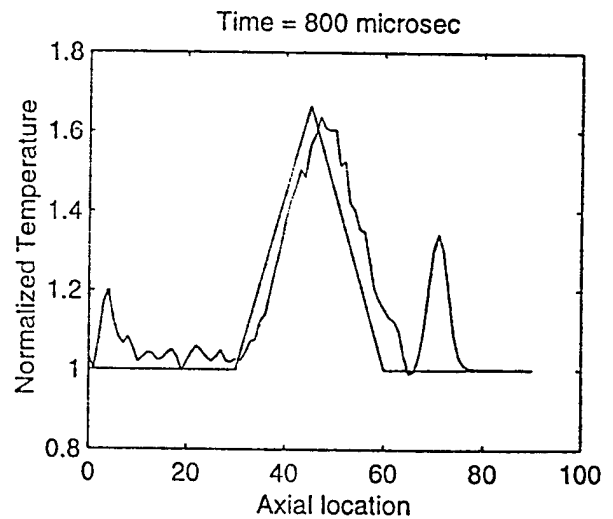
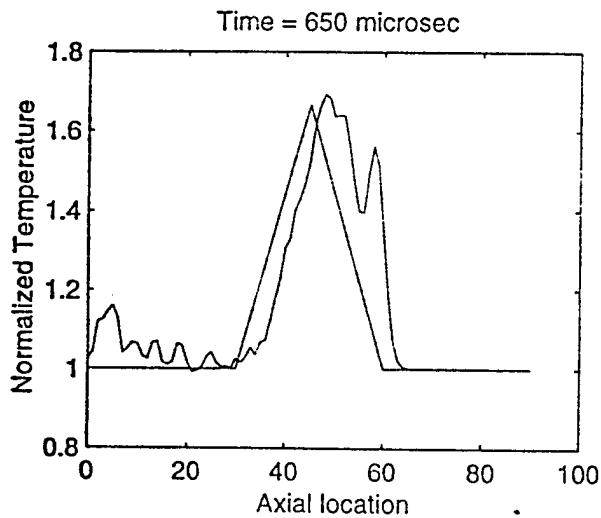
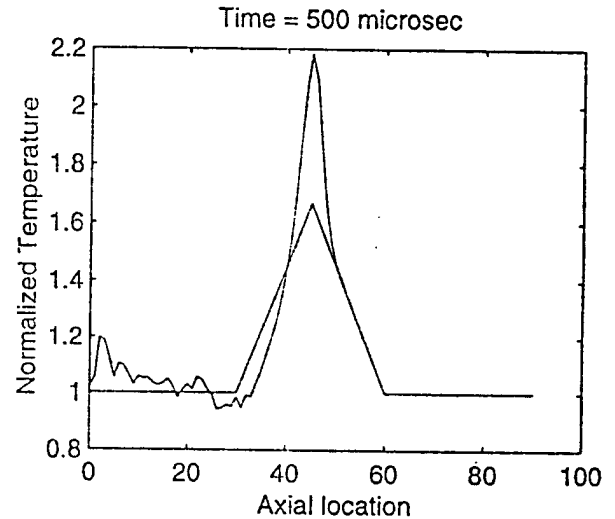
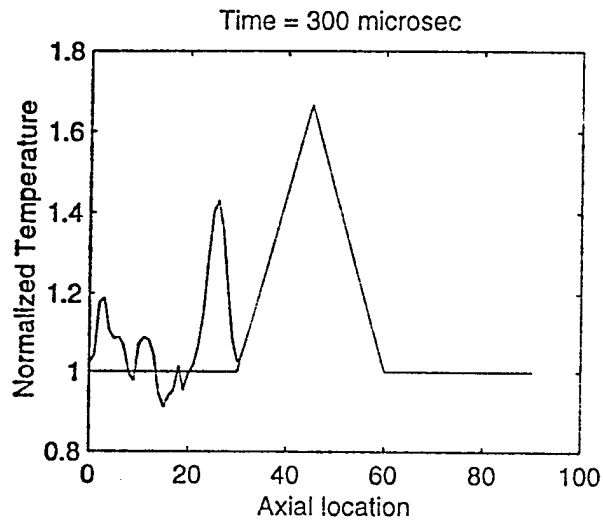
CASE III



1/8/98

- 1) No radial temp g.
- 2) Triangular axial temp gra
- 3) No plasma

CASE III



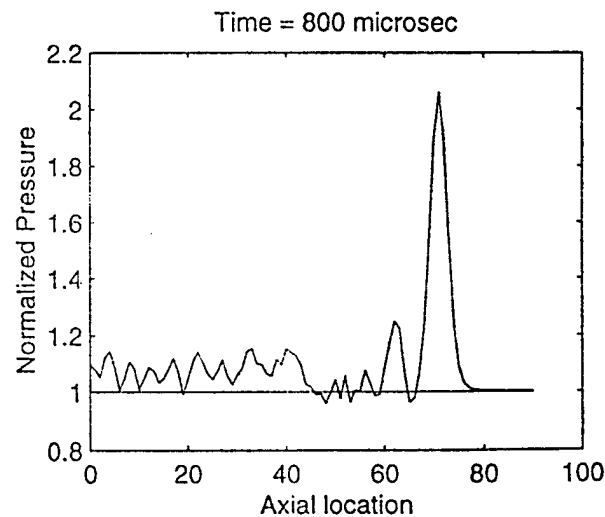
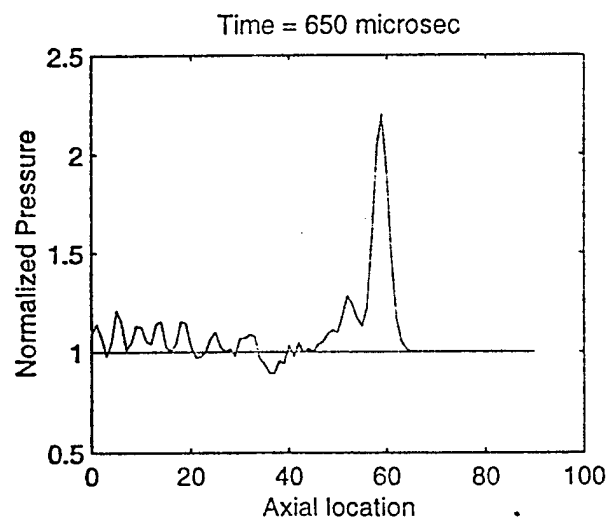
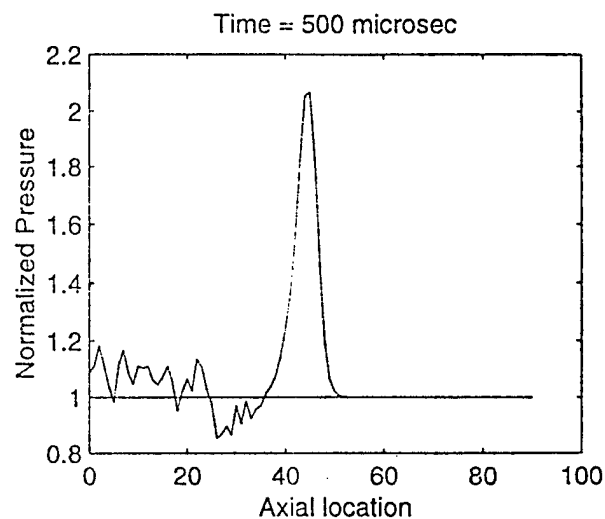
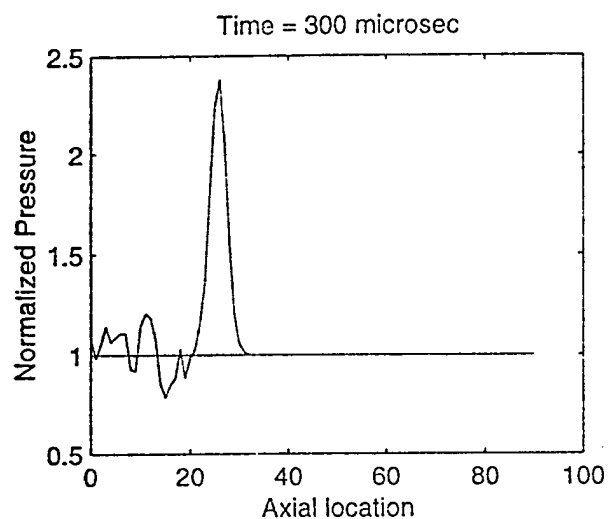
1/8/98

1) No radial
temp gradient

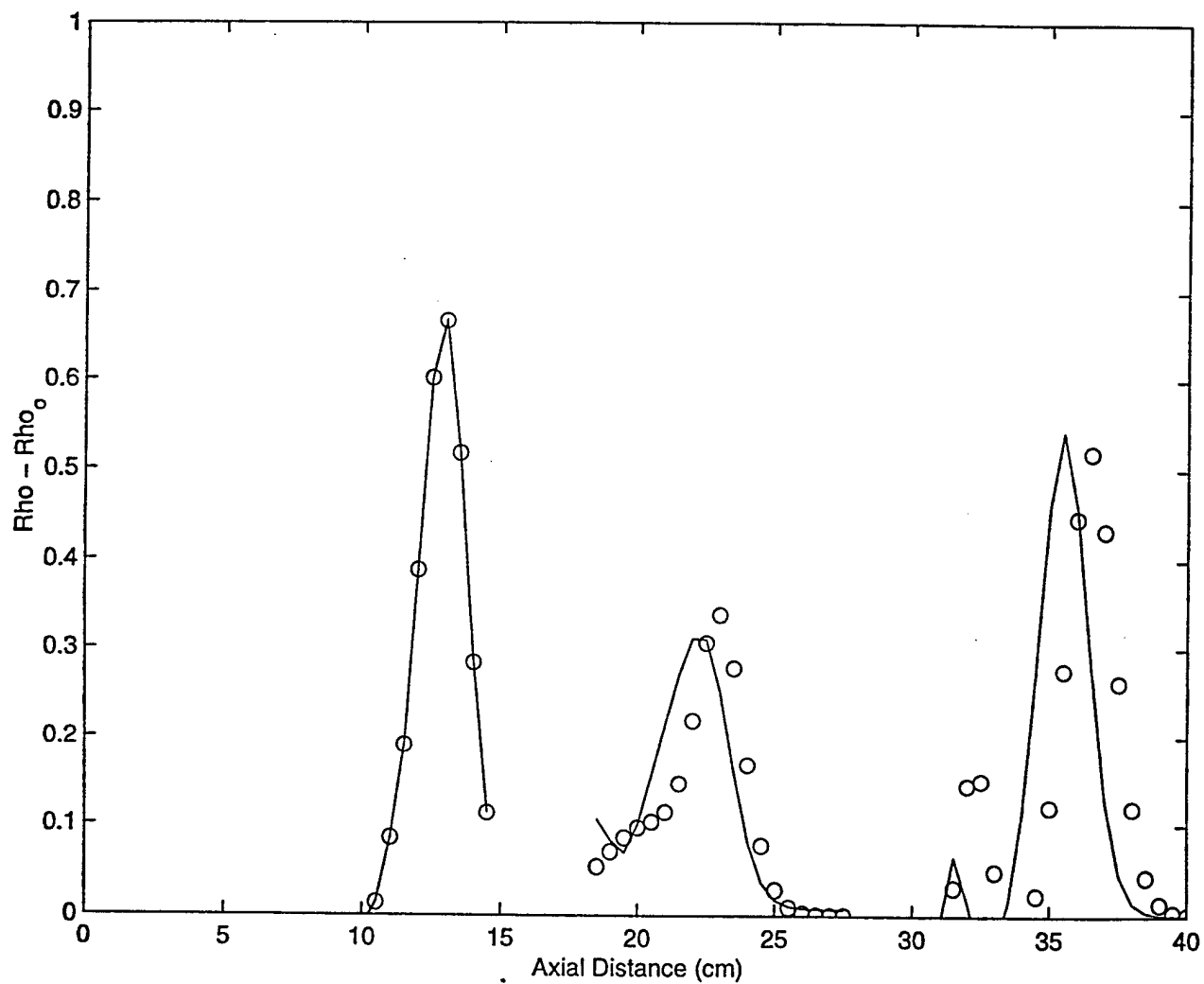
2) Triangular
axial temp grad

3) No plasma

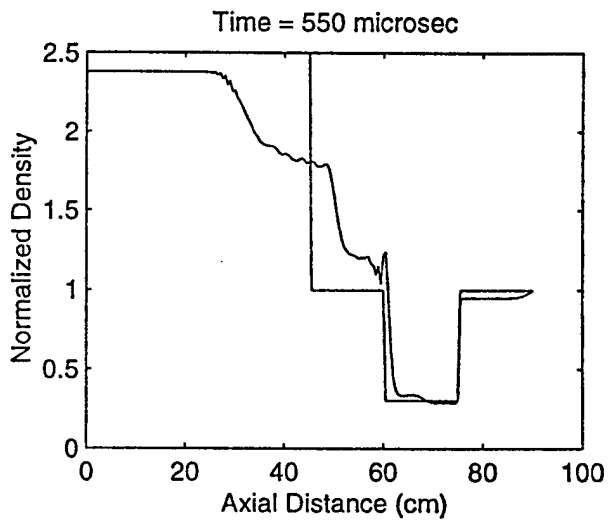
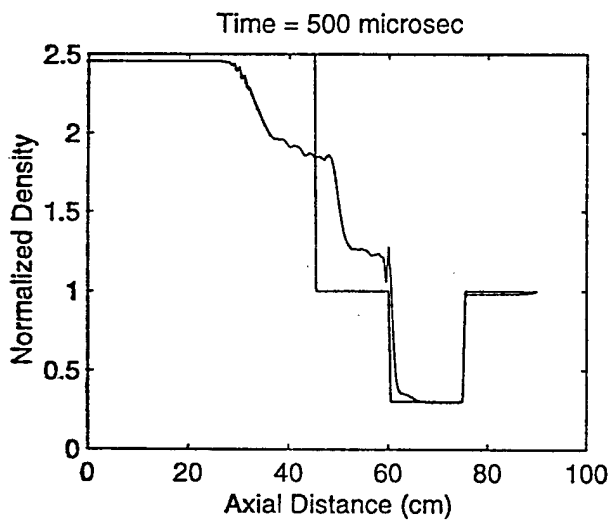
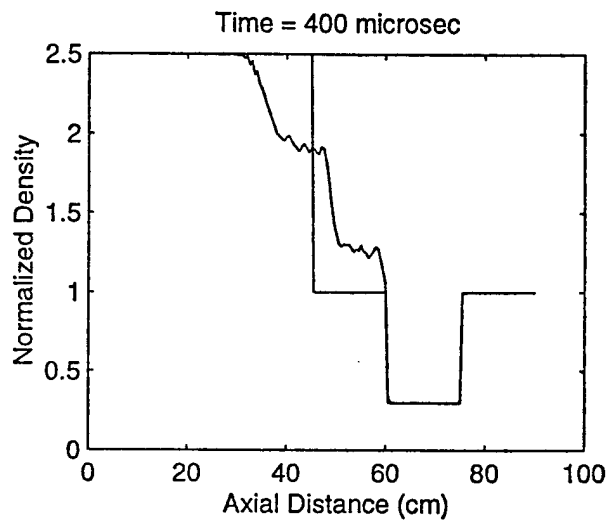
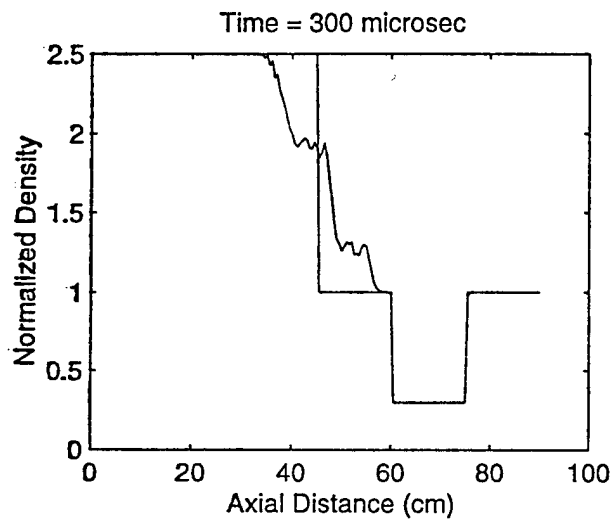
CASE III

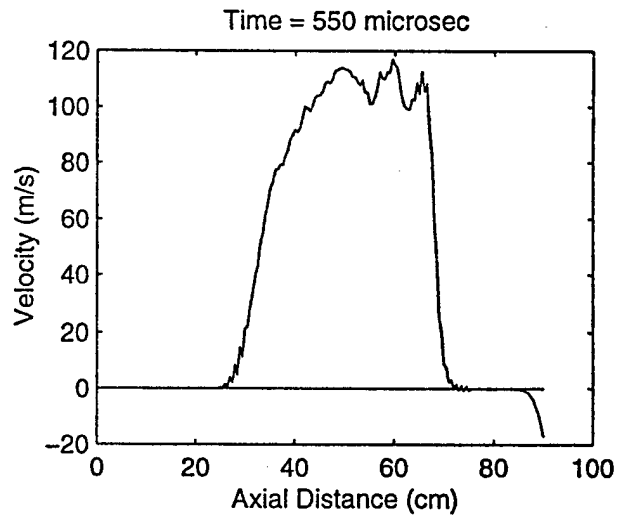
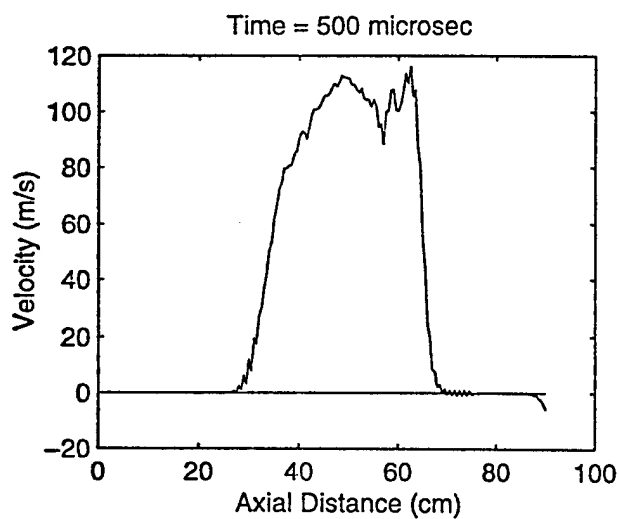
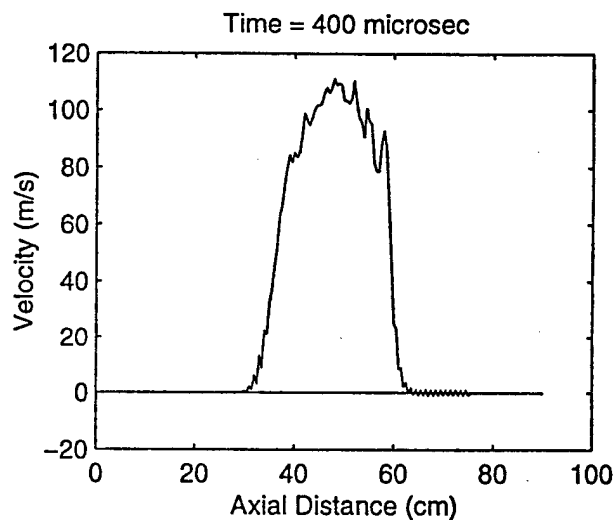
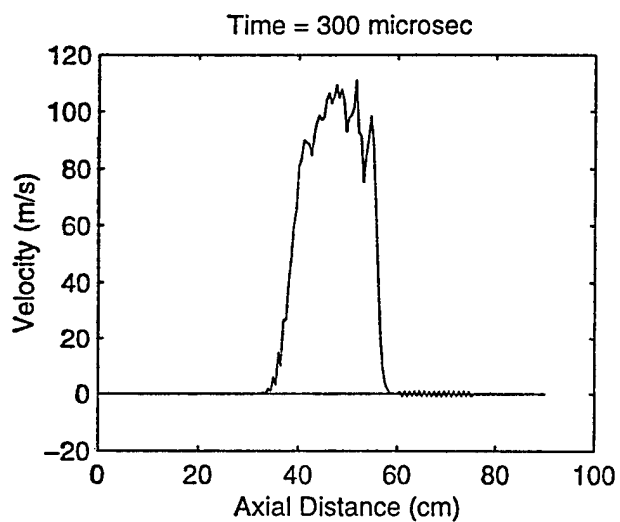


501
350/4000/350
u
-
3/0
u/

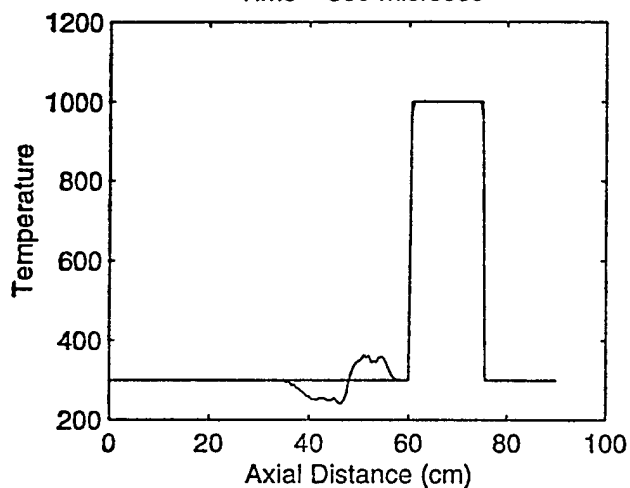


DIAPHRAGM/PISTON - DRIVEN STACK

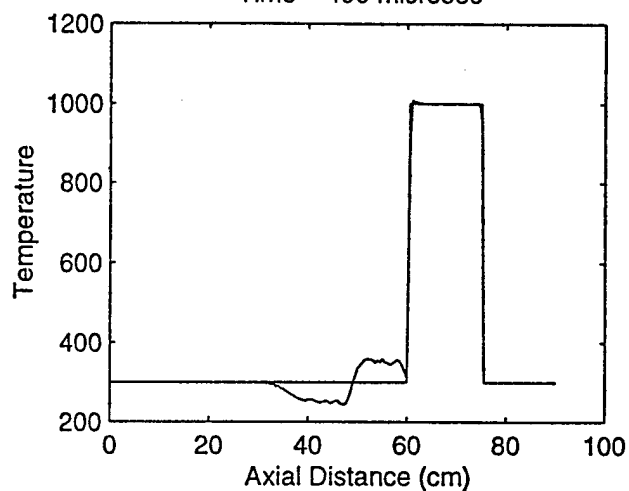




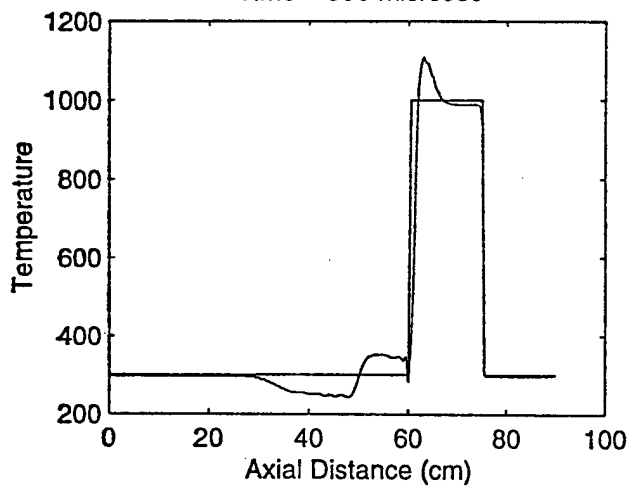
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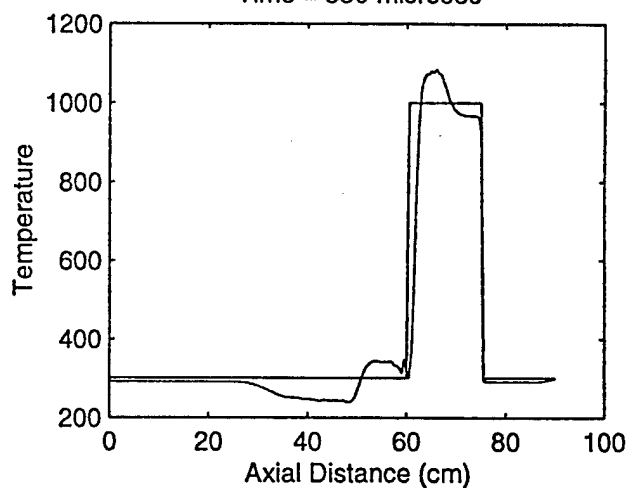
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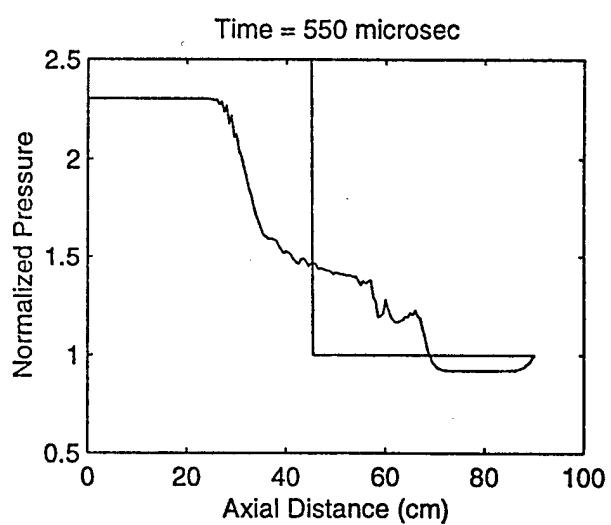
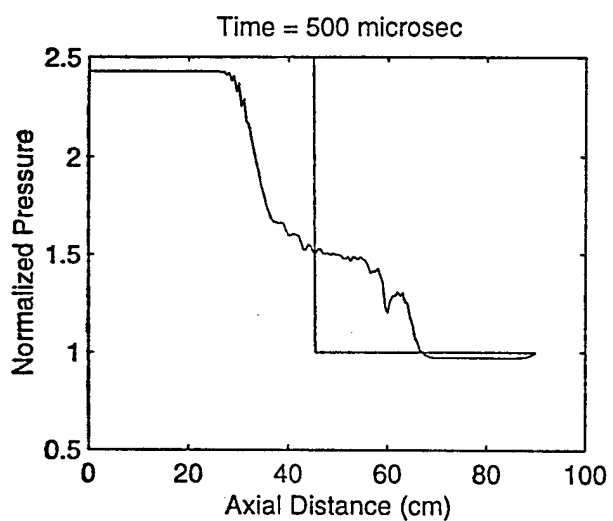
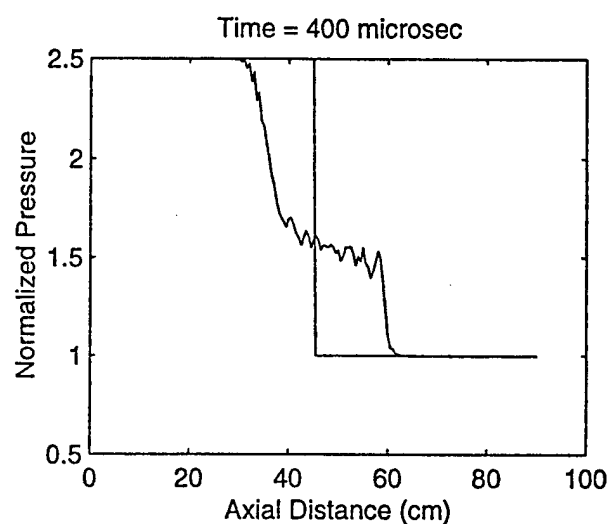
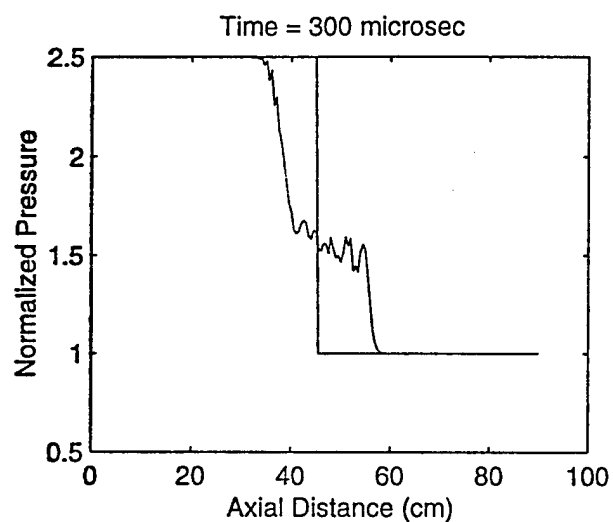


Time = 500 microsec

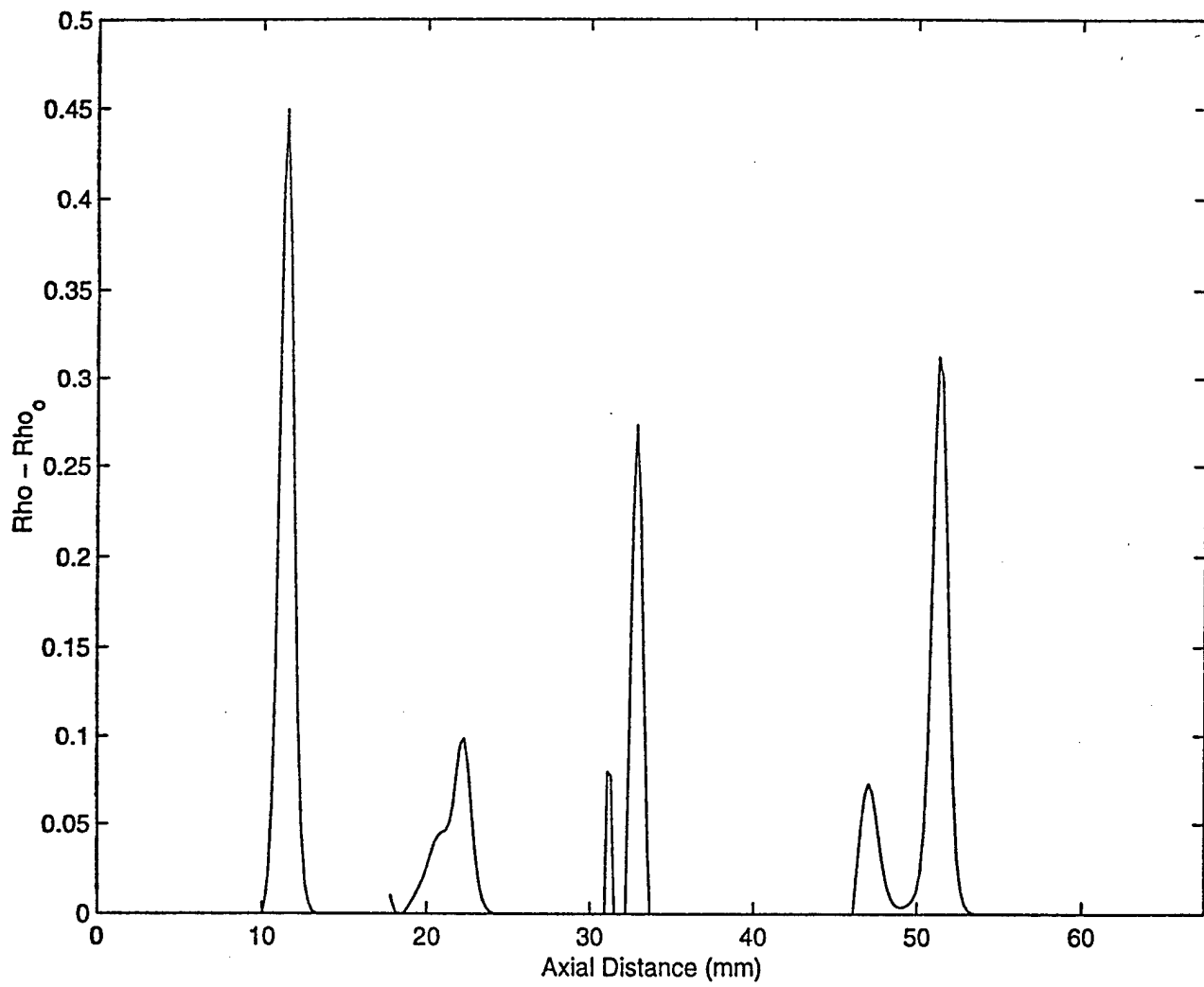


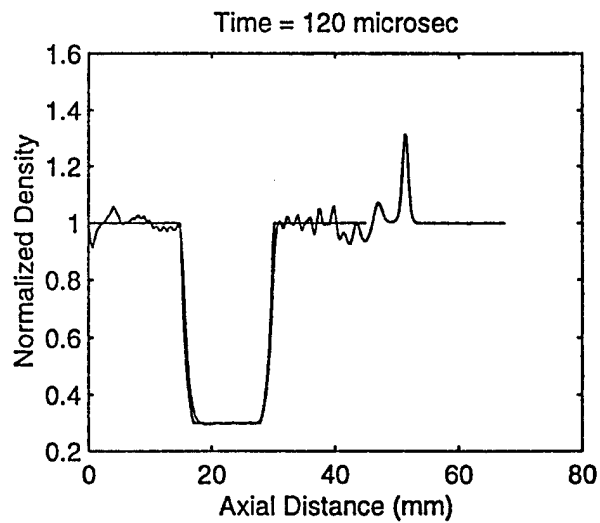
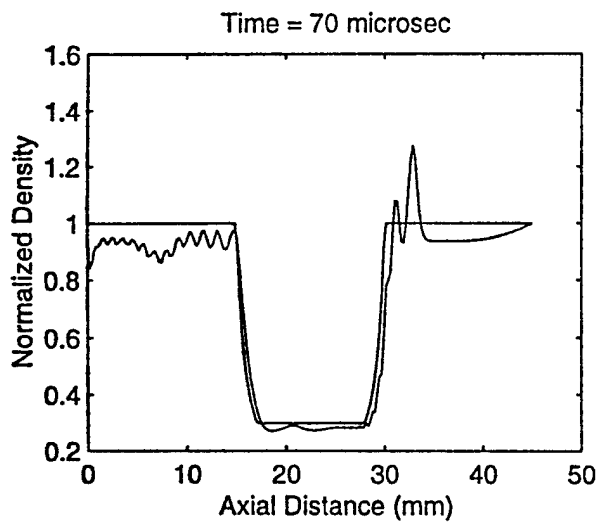
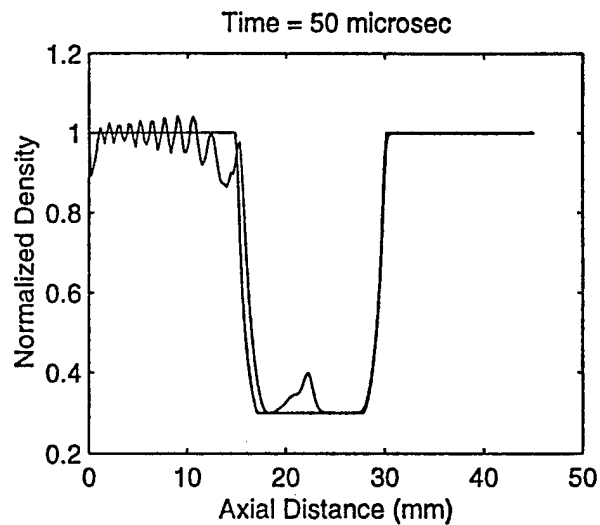
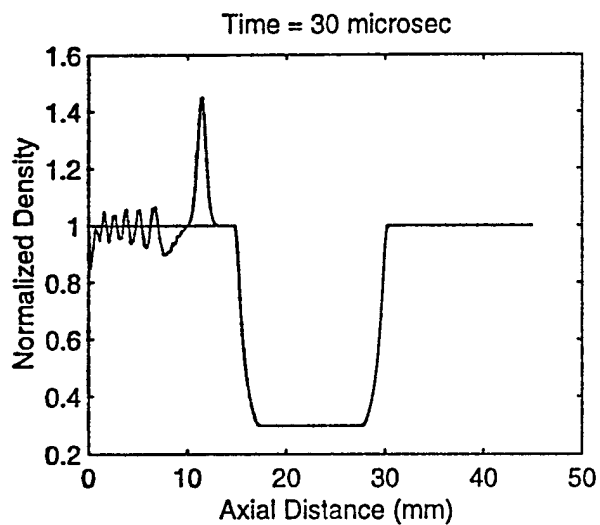
Time = 550 microsec





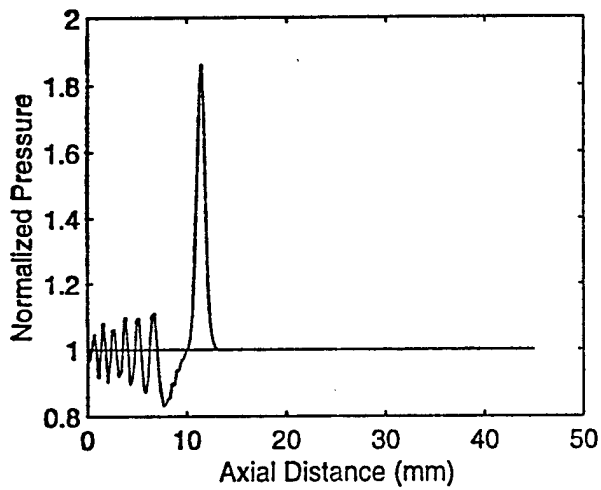
FINE GRID, 0.001000/3.00



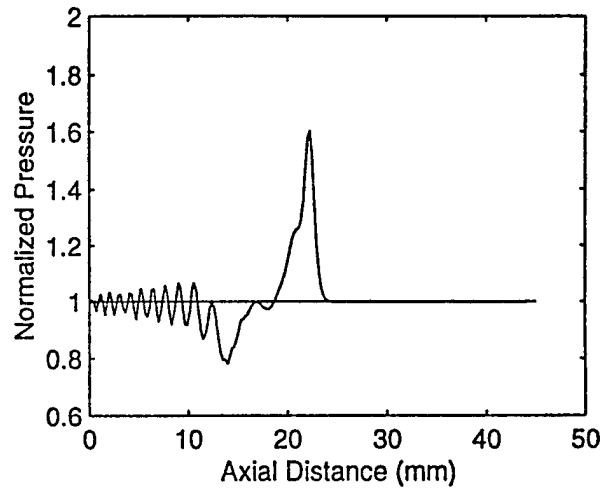


FIVE 4.2.0, 30/100/3.50

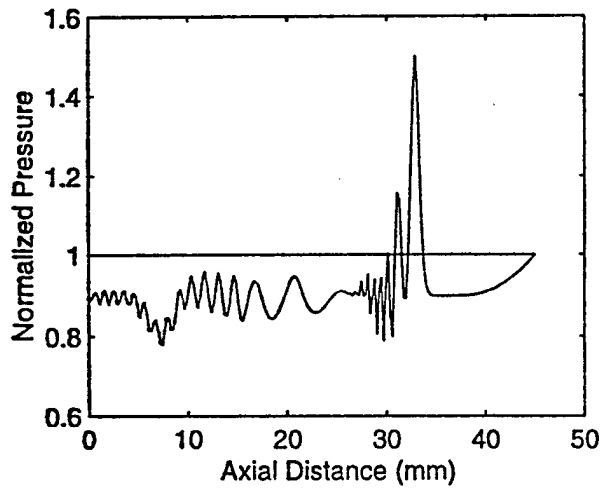
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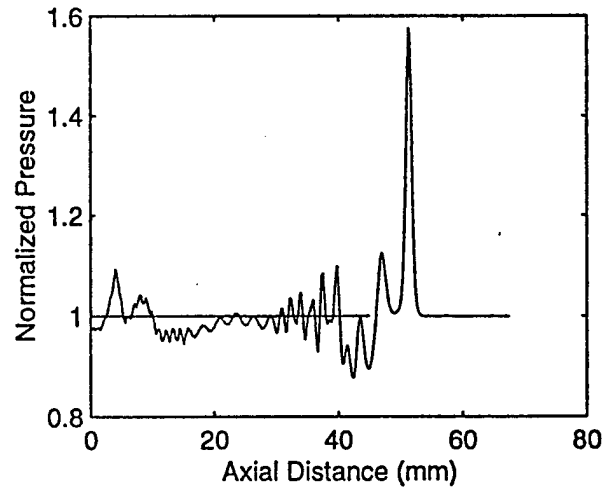
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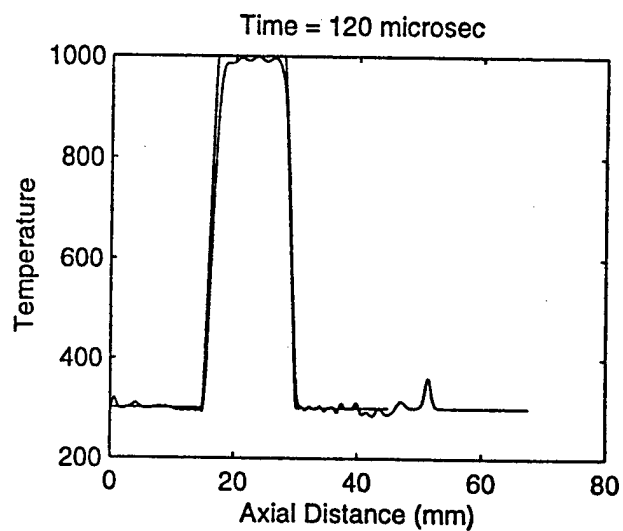
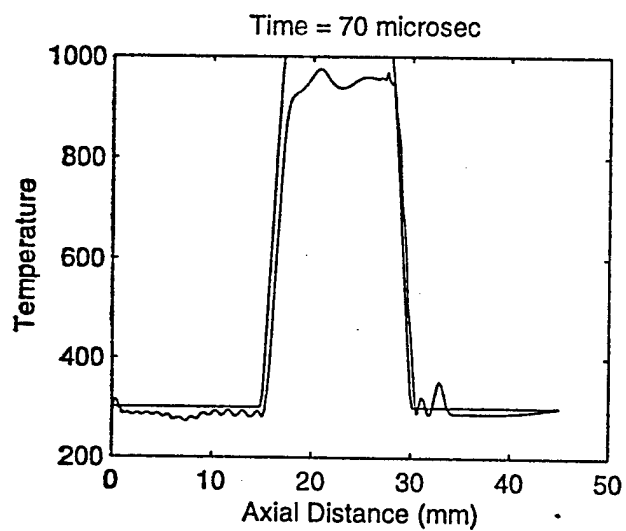
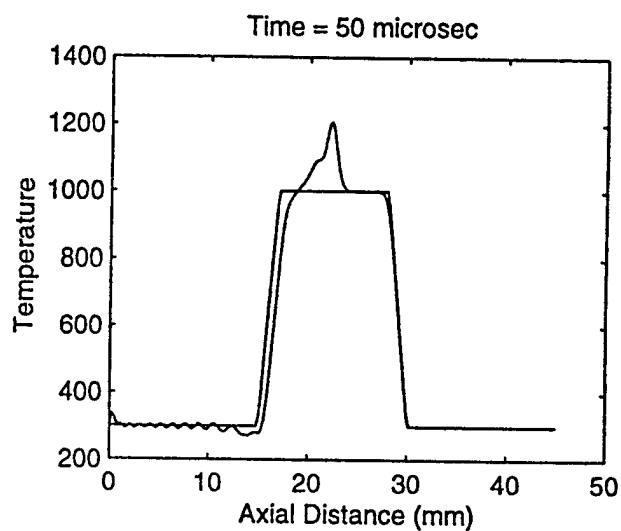
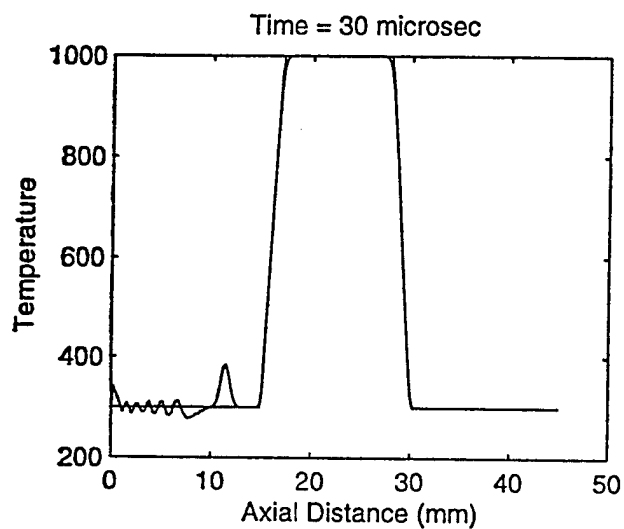


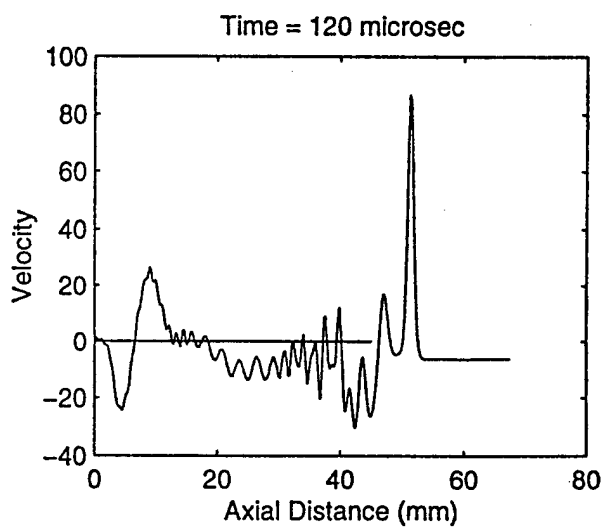
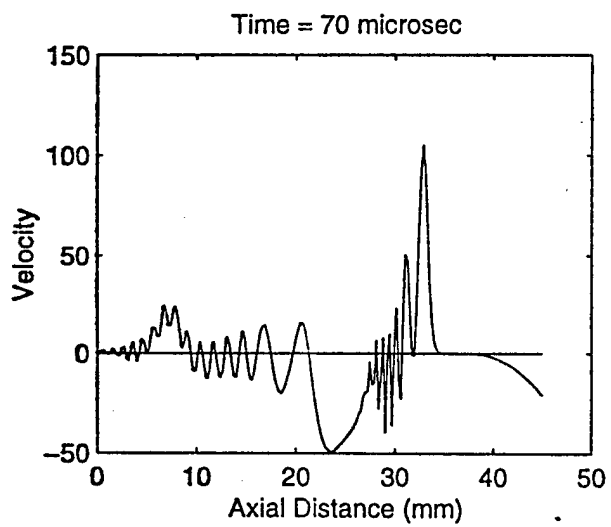
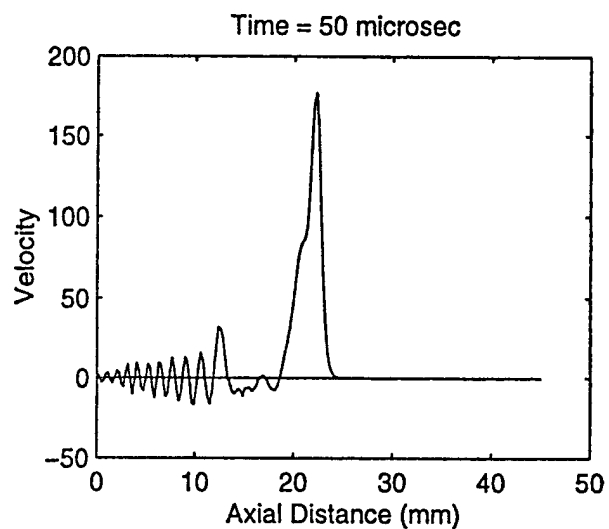
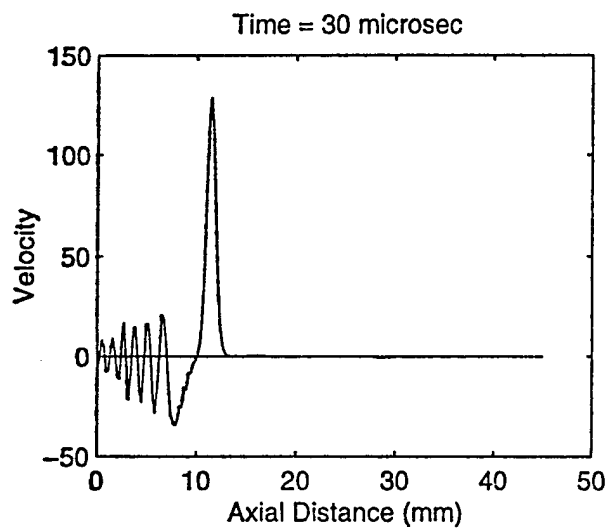
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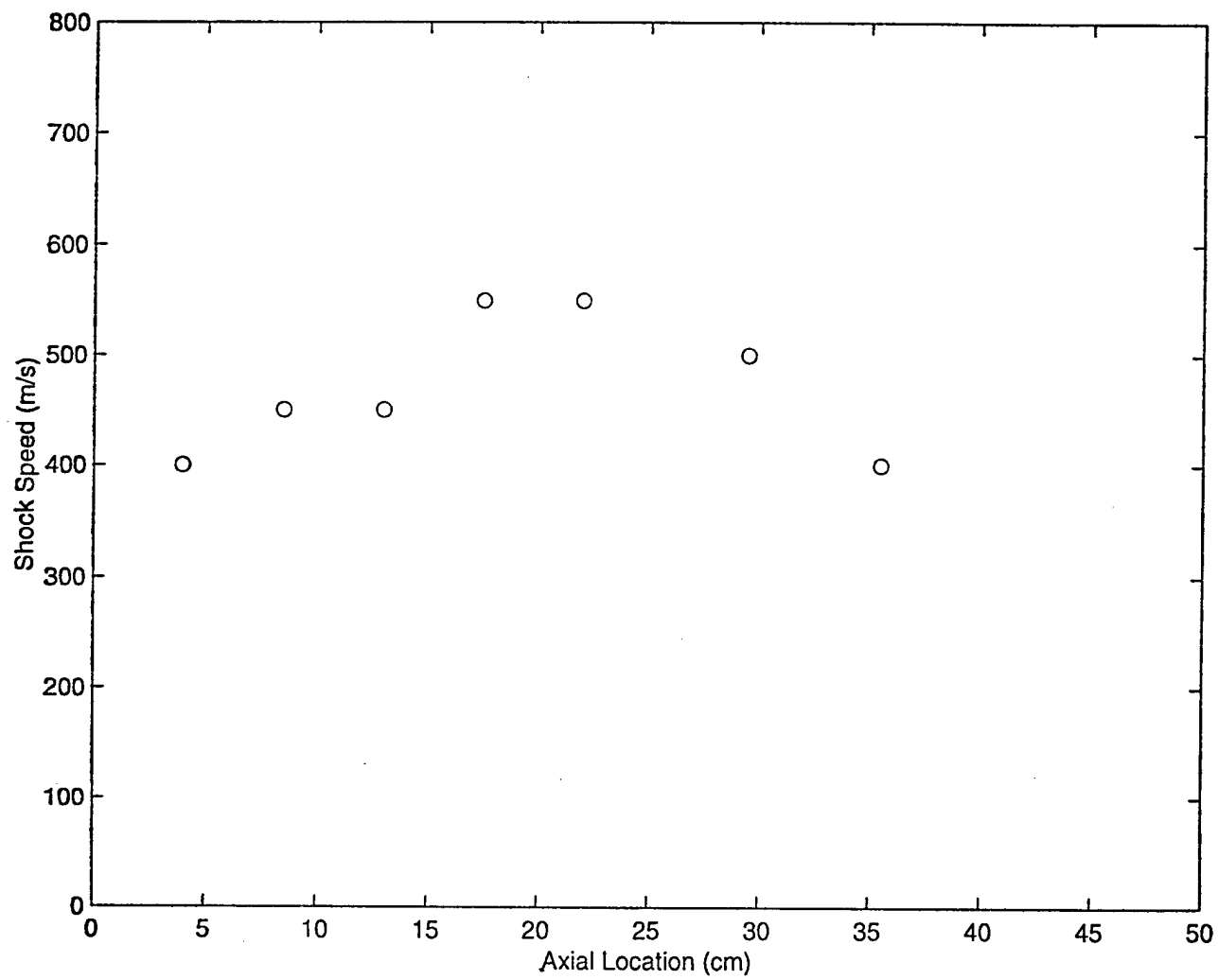


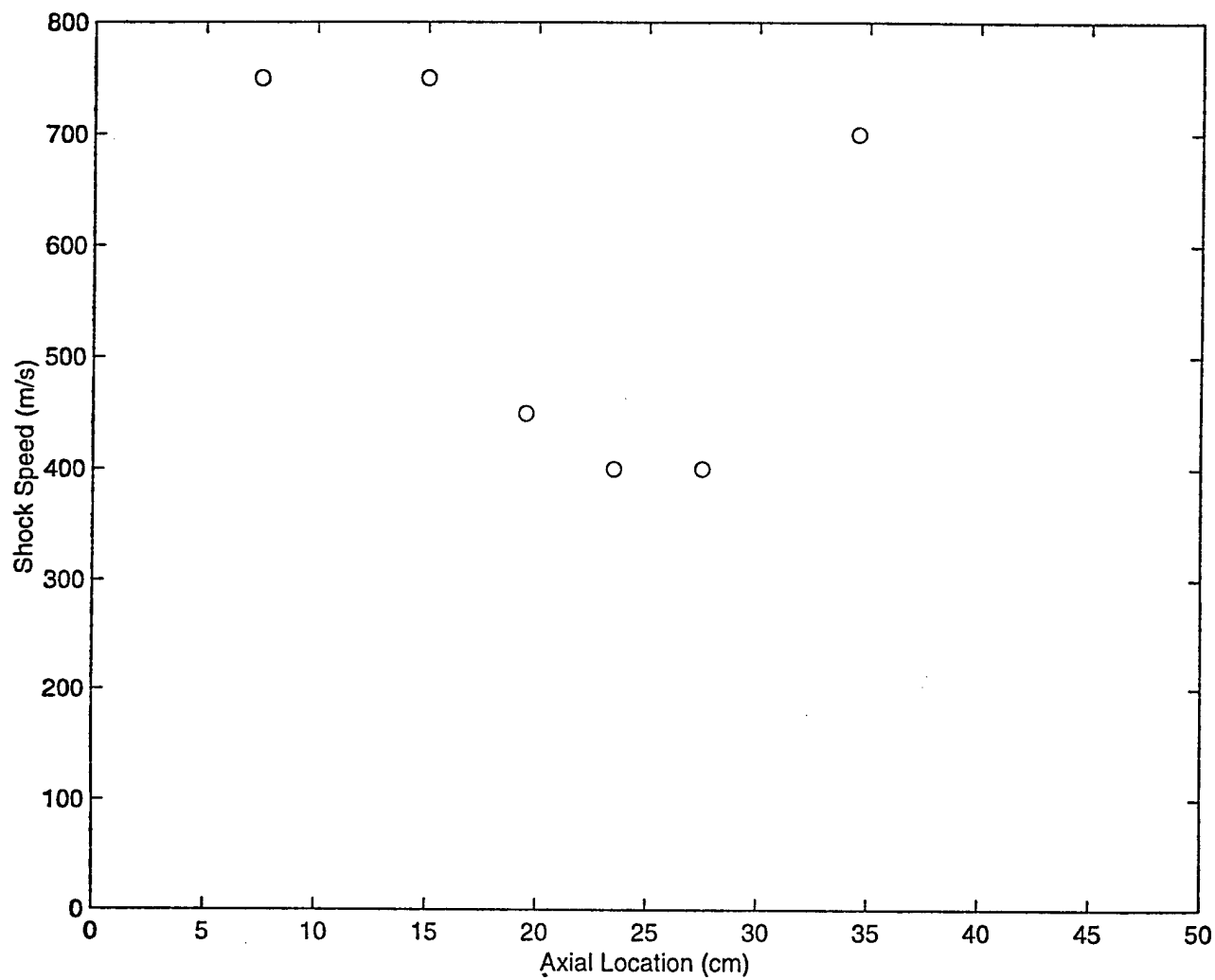
Time = 120 microsec







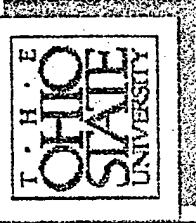




Summary of Thermal Effects

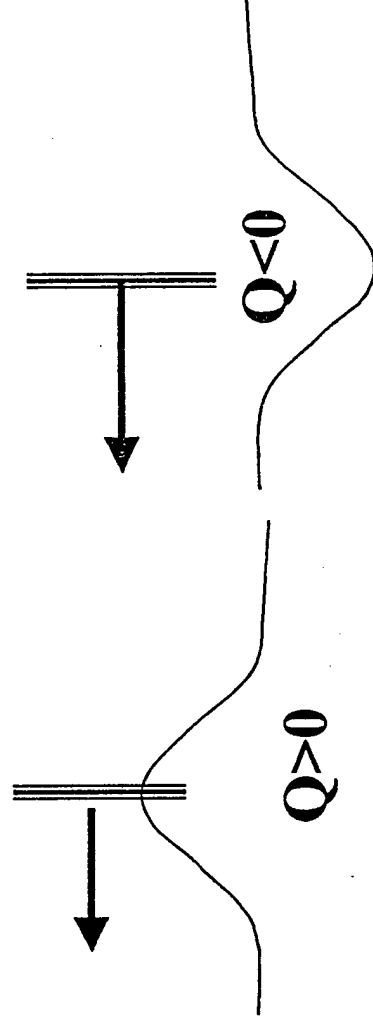
- Axial temperature gradients cause splitting of an impulsive load into two distinct waves, a strong leader, and a weak follower.
- Radial gradients affect results quantitatively, but are not the cause of this splitting.
- Shock recovery is almost immediate, whereas they vary from 10 cm to 20 cm in the Ganguly-Bletzinger experiments.

∴ THERMAL EFFECTS CANNOT SOLELY EXPLAIN OBSERVED EXPERIMENTAL RESULTS.

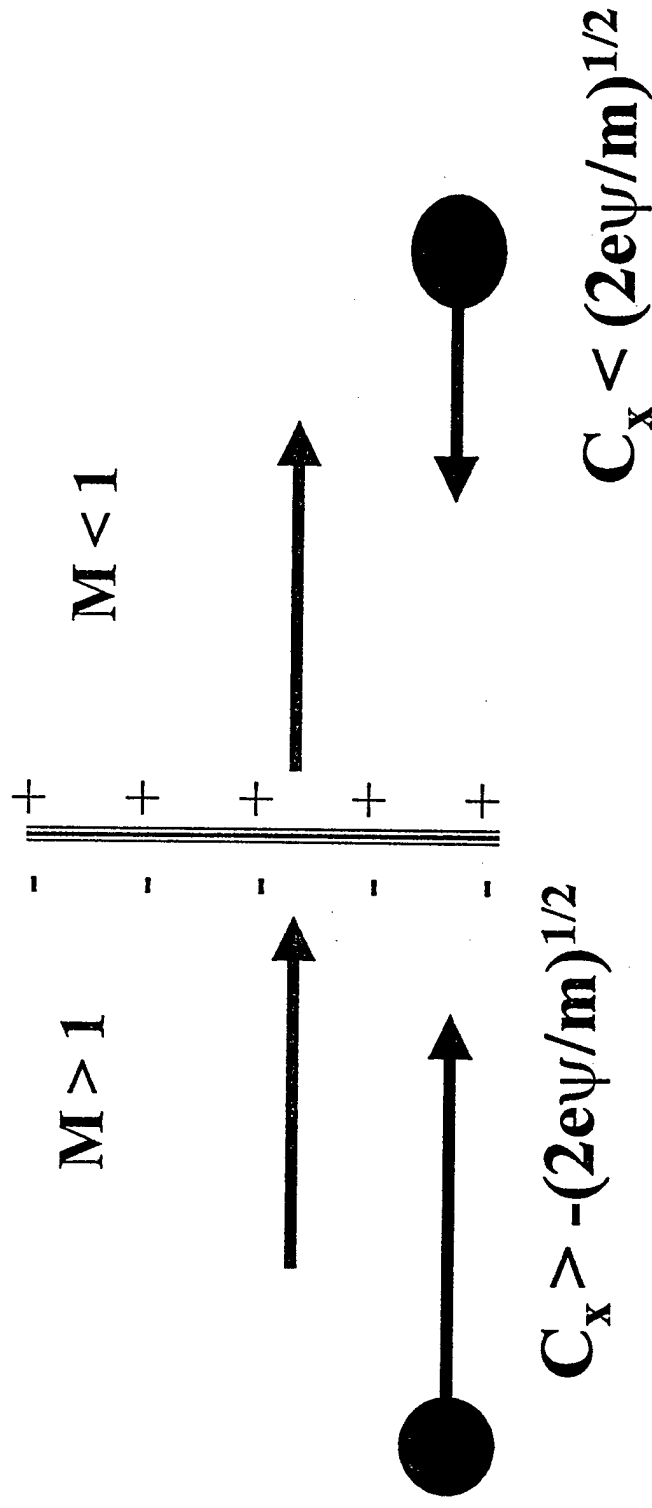


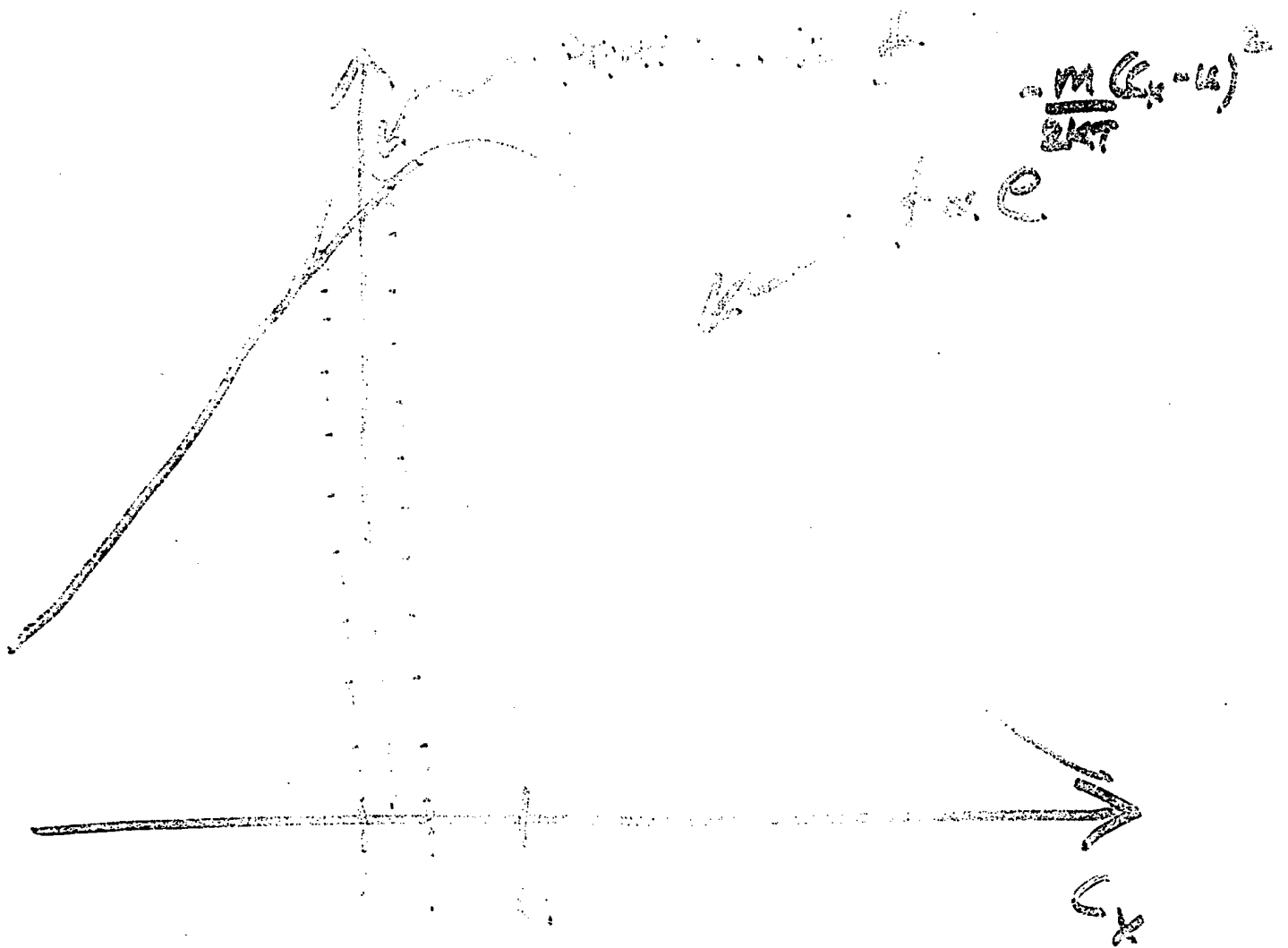
- **Previous analysis (Adamovich et. al.) shows:**

- (1) In order to change shock structure, an agent must have energy comparable to the incident kinetic energy density of the incident flow
- (2) Two globally adiabatic shocks, able to exchange energy among themselves reproduces experimental observations:



Suppose that space charge layer induces a potential in the neutral gas, because neutrals are polarizable:





CONTRIBUTION
TO
LEFTWARD
FLUX

CONTRIBUTION TO
RIGHTWARD FLUX

$$+\sqrt{\frac{2kT}{m}}$$

$$-\sqrt{\frac{2kT}{m}}$$

Consequences

- Let the force experienced by the neutral particles be:

$$F_x = -e \left(\frac{\partial \psi}{\partial x} \right) \left[\mathfrak{S} \left(\sqrt{\frac{2e\psi}{m}} - C_x \right) \mathfrak{S}(x - x_o) + \mathfrak{S} \left(\sqrt{\frac{2e\psi}{m}} + C_x \right) \mathfrak{S}(x_o - x) \right]$$

where

$$\mathfrak{S}(z) = \begin{cases} 0, & z < 0 \\ 1, & z > 0 \end{cases} \text{ is the Heaviside step function,}$$

and C_x is the x -component of the absolute particle velocity

What would be the corresponding macroscopic equations to lowest order?

- Continuity

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial x}(nu) = N = \left\{ \begin{array}{l} \frac{ne}{m} \left(\frac{\partial \psi}{\partial x} \right) \sqrt{\frac{m}{2\pi kT}} - \left(\sqrt{\frac{e\psi}{kT}} - u \sqrt{\frac{m}{2kT}} \right)^2 e ; x > x_0 \\ - \frac{ne}{m} \left(\frac{\partial \psi}{\partial x} \right) \sqrt{\frac{m}{2\pi kT}} - \left(\sqrt{\frac{e\psi}{kT}} + u \sqrt{\frac{m}{2kT}} \right)^2 e ; x < x_0 \end{array} \right.$$

Source terms in continuity equation

$$N_1 \approx \frac{en_1}{m} \left(\frac{\partial \psi}{\partial x} \right) \Big|_1 \sqrt{\frac{m}{2\pi kT_1}} e^{-\frac{\gamma}{2} M_1^2}$$

$$N_2 \approx -\frac{en_2}{m} \left(\frac{\partial \psi}{\partial x} \right) \Big|_2 \sqrt{\frac{m}{2\pi kT_2}} e^{-\frac{\gamma}{2} M_2^2}$$

$$\frac{N_2}{N_1} \approx -\frac{n_2}{n_1} \frac{(\partial \psi / \partial x)|_2}{(\partial \psi / \partial x)|_1} \sqrt{\frac{T_1}{T_2}} e^{\frac{\gamma}{2} (M_1^2 - M_2^2)}$$

$$\Rightarrow N_2 > N_1$$

• X-momentum

$$\frac{\partial(nu)}{\partial t} + \frac{\partial}{\partial x} \left(nu^2 + \frac{nkT}{m} \right) = M =$$

$$\left\{ \begin{aligned} & \frac{en}{m} \left(\frac{\partial \psi}{\partial x} \right) \left[\sqrt{\frac{e\psi}{\pi kT}} e^{-\left(\sqrt{\frac{e\psi}{kT}} - u \sqrt{\frac{m}{2kT}} \right)^2} \right. \\ & \quad \left. - \frac{1}{2} \left[1 - \operatorname{erf} \left(u \sqrt{\frac{m}{2kT}} - \sqrt{\frac{e\psi}{kT}} \right) \right] \right] \right] \quad ; x > x_0 \\ & \frac{en}{m} \left(\frac{\partial \psi}{\partial x} \right) \left[\sqrt{\frac{e\psi}{\pi kT}} e^{-\left(\sqrt{\frac{e\psi}{kT}} + u \sqrt{\frac{m}{2kT}} \right)^2} \right. \\ & \quad \left. - \frac{1}{2} \left[1 - \operatorname{erf} \left(-u \sqrt{\frac{m}{2kT}} - \sqrt{\frac{e\psi}{kT}} \right) \right] \right] \right] \quad ; x < x_0 \end{aligned} \right.$$

Source term in momentum equation

$$M_1 \approx -\frac{en_1}{m} \left(\frac{\partial \psi}{\partial x} \right) \Big|_1 e^{-\frac{\gamma}{2} M_1^2}$$

$$M_2 \approx -\frac{en_2}{m} \left(\frac{\partial \psi}{\partial x} \right) \Big|_2 e^{-\frac{\gamma}{2} M_2^2}$$

$$\Rightarrow \left| \frac{M_2}{M_1} \right| \approx \frac{n_2}{n_1} \frac{(\partial \psi / \partial x) \Big|_2}{(\partial \psi / \partial x) \Big|_1} e^{\frac{\gamma}{2} (M_1^2 - M_2^2)}$$

\Rightarrow **Net Force is upstream**

• Energy

$$\frac{\partial}{\partial t} \left(\frac{3}{2} nkT + \frac{1}{2} mnu^2 \right) + \frac{\partial}{\partial x} \left(\frac{5}{2} nukT + \frac{1}{2} mnu^3 \right) = S$$

$$\left\{ \begin{aligned} & ne \left(\frac{\partial \psi}{\partial x} \right) \left[\left(\frac{2kT}{m\pi} \right)^{1/2} + \left(\frac{e\psi}{kT} \right) \left(\frac{kT}{2\pi m} \right)^{1/2} \right] e^{-\left(\sqrt{\frac{e\psi}{kT}} - u \sqrt{\frac{m}{2kT}} \right)^2} \\ & - \frac{neu}{2} \left(\frac{\partial \psi}{\partial x} \right) \left[1 - \operatorname{erf} \left(u \sqrt{\frac{m}{2kT}} - \sqrt{\frac{e\psi}{kT}} \right) \right] \end{aligned} \right\} ; x > x_0$$

$$\left\{ \begin{aligned} & - ne \left(\frac{\partial \psi}{\partial x} \right) \left[\left(\frac{2kT}{m\pi} \right)^{1/2} + \left(\frac{e\psi}{kT} \right) \left(\frac{kT}{2\pi m} \right)^{1/2} \right] e^{-\left(\sqrt{\frac{e\psi}{kT}} + u \sqrt{\frac{m}{2kT}} \right)^2} \\ & - \frac{neu}{2} \left(\frac{\partial \psi}{\partial x} \right) \left[1 - \operatorname{erf} \left(-u \sqrt{\frac{m}{2kT}} - \sqrt{\frac{e\psi}{kT}} \right) \right] \end{aligned} \right\} ; x < x_0$$

where $S =$

Source term in energy equation

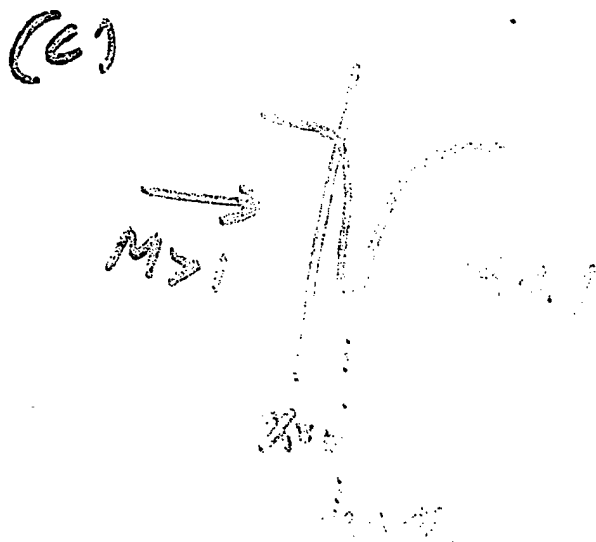
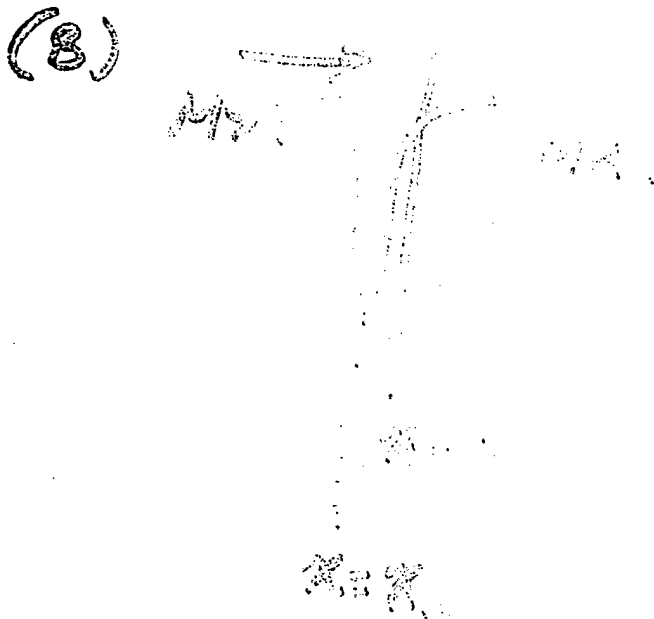
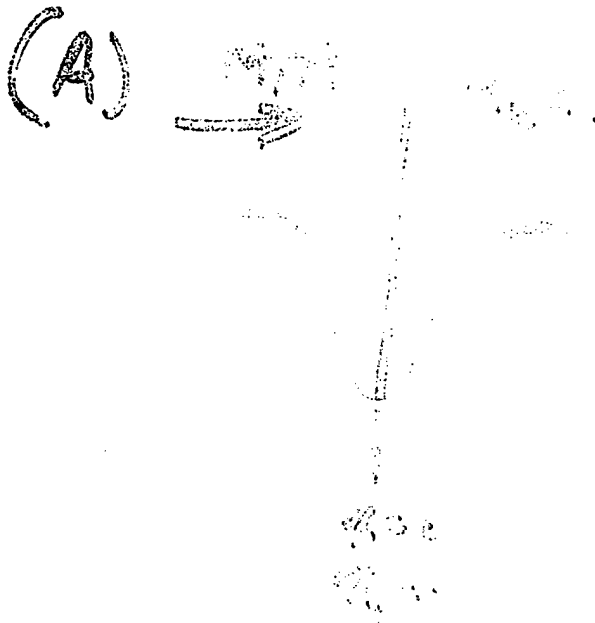
$$S_1 \approx en_1 \left(\frac{\partial \psi}{\partial x} \right) \Big|_1 \left(\frac{\gamma k T_1}{m \pi} \right)^{1/2} \left[\sqrt{\frac{2}{\gamma}} - M_1 \right] e^{-\frac{\gamma}{2} M_1^2}$$

$$S_2 \approx -en_2 \left(\frac{\partial \psi}{\partial x} \right) \Big|_2 \left(\frac{\gamma k T_2}{m \pi} \right)^{1/2} \left[\sqrt{\frac{2}{\gamma}} + M_2 \right] e^{-\frac{\gamma}{2} M_2^2}$$

$$\Rightarrow \frac{S_2}{S_1} \approx \frac{n_2}{n_1} \frac{(\partial \psi / \partial x) \Big|_2}{(\partial \psi / \partial x) \Big|_1} \sqrt{\frac{T_2}{T_1}} \left[\frac{\sqrt{\frac{2}{\gamma}} + M_2}{M_1 - \sqrt{\frac{2}{\gamma}}} \right] e^{\frac{\gamma}{2} (M_1^2 - M_2^2)}$$

$$\Rightarrow \text{Note change in sign when } M_1 = \sqrt{\frac{2}{\gamma}}$$

THREE CASES



Case(B): Potential well ahead of shock

- Just upstream of the shock, for $x_0 < x < 0$, $S > 0$, provided M_1 in the region is less than $(2/\gamma)^{1/2}$ while $S \rightarrow 0$ for $x > 0$ (downstream of the shock) since $\partial\psi/\partial x \rightarrow 0$ there
 \Rightarrow SPLITTING ?
- For $M_1 > (2/\gamma)^{1/2}$, $S < 0$ in the same region
 \Rightarrow STABLE
- Further, $\tilde{M} < 0$ for $x > x_0 \Rightarrow$ a body force driving shock upstream is present
 \Rightarrow LARGER STAND-OFF DISTANCE

- **Distribution function will be non-M-B in the neighborhood of the shock**
 \Rightarrow steep thermal, and density gradients, will induce additional mass, momentum, and energy transfer from downstream region to upstream region.
- **Questionable as to whether a steady state can exist when sources are present in continuity, momentum, and energy equations.**

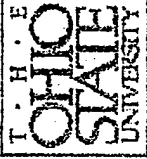
Summary

- Classical gas dynamics predicts splitting of a pulse in the presence of a streamwise temperature gradient - But, split structure appears different from that observed in experiments.
- There may be special circumstances under which induced dipole effects cause the presence of local adverse thermal gradients at the shock front, by affecting the distribution function.



Introduction

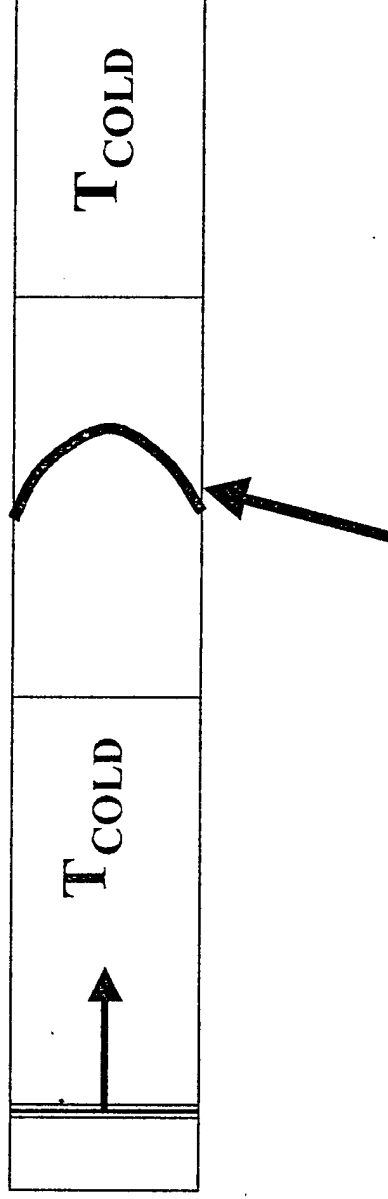
- **Anomalous behavior of shock waves in weakly ionized plasmas:**
 - shock wave accelerates
 - stand-off distance increases
 - shock splits into two or more structures
 - shock strength (as measured by density differences) diminishes
 - results occur in atomic and molecular gases
 - shock nearly recovers its original strength well downstream of the discharge.



- **Previous simulations (Bailey & Hilbun, Macheret & Martinelli) show radial thermal gradients can alter density profiles:**
 - **in piston-driven shock tubes**
 - **and when there is a curved boundary initially separating the hot and cold regions of a gas**
- **Thermal effects have been invoked to explain some experimental observations, but cannot explain others (such as shock recovery distance).**



Effects of Radial Thermal Gradients (2-D axi-symmetric Navier-Stokes solution for Argon)



Initial parabolic temperature profile
varying from T_{HOT} at the centerline to
 T_{COLD} at the wall.

Flow Control via MHD and EMHD

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<http://www.cfm.brown.edu/CRUNCH>

AFOSR Workshop on

Understanding and Control of Ionized High-Speed Flows

February 26–27, 1998

Princeton, NJ

High-Speed Flow Features

- Strong shock wave effects/interactions

- thin layers, small detachment distance, entropy layer

- Strong viscous effects/interactions

- $\delta \sim \frac{M^2}{\sqrt{Re}}$

- increased drag, heating at leading edge

- Transitional flow

- $Re_c \sim 10^8$ vs. 10^5 (subsonic)

- C_f and C_H are $3 \times$ laminar

- $Re_c^0 \sim 100M_e$

- Nonequilibrium

- thermal, chemical

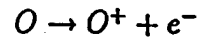
- introduction of length scale

- multi-rate physics

- Ionization

- 4000 K to 6000 K: $NO \rightarrow NO^+ + e^-$ (mild)

- > 9000 K: $N \rightarrow N^+ + e^-$



- Above 20km + 10 km/s

- External B, E , frequencies

- Multiple boundary layers

- hydrodynamics, thermal, species

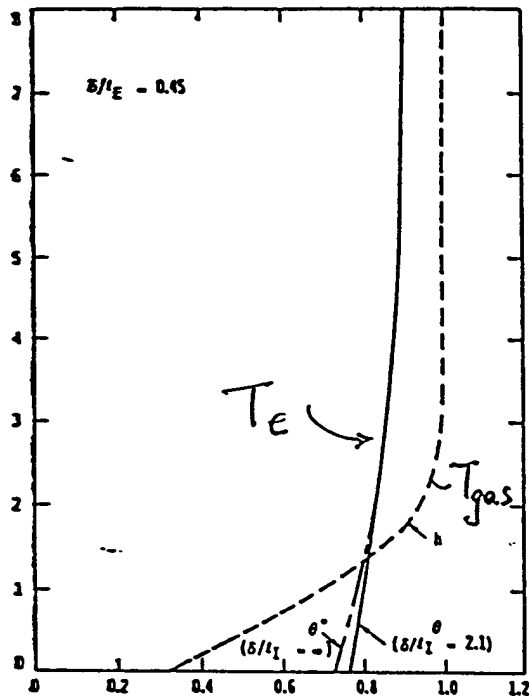
- electric conductivity, entropy layers

\therefore - Multi-Rate Physics

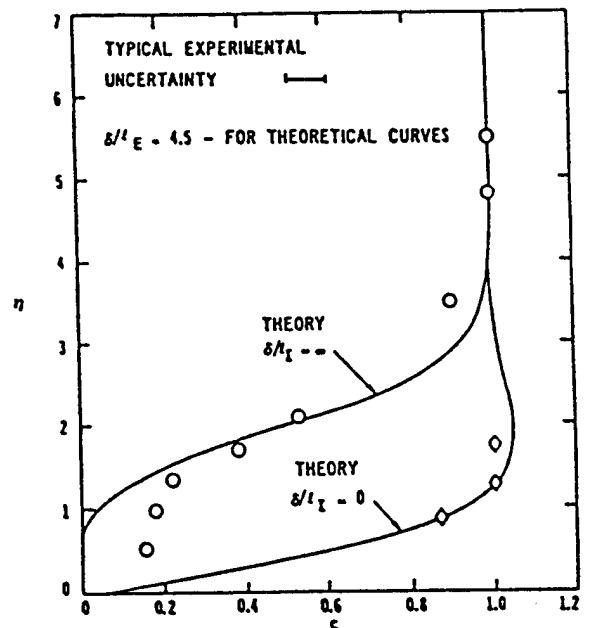
- Multiple BLs

Non-Equilibrium Plasma Boundary Layer

- Effects on T_e, σ
- atmospheric-pressure potassium-seeded argon plasma



Normalized Temperature



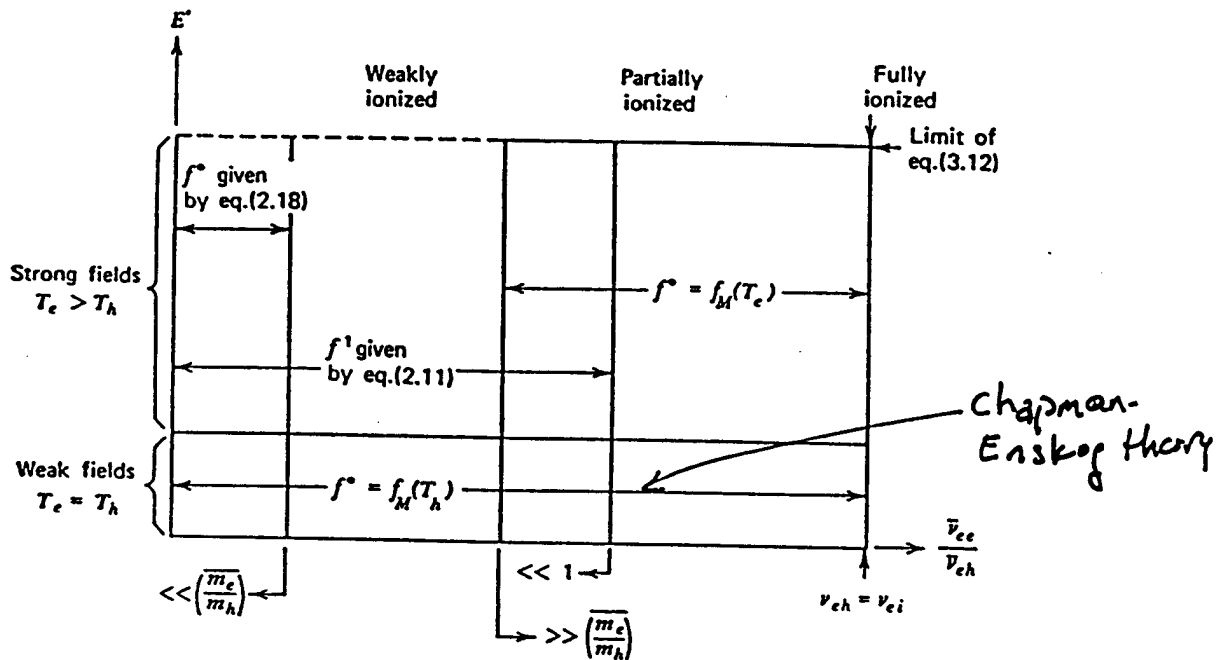
Normalized Conductivity

Ref: Brown & Mitchner (1971)

"... Even in plasma which is strongly collision dominated, significant nonequilibrium may be present in the boundary layer adjacent to a cooled solid surface..."

Note: Joule heating due to E could further increase conductivity.

Electrical Conductivity



Electric Field vs. Ionization

- In constant E, B fields tensor conductivity

$$\text{Weakly-ionized} \begin{cases} \sigma_{\parallel} = \mathcal{F}(n_e, m_e, \nu_{eH}, f^0) \\ \sigma_{\perp} = \mathcal{F}(n_e, m_e, \nu_{eH}, f^0, \omega_e) \\ \sigma_H = \mathcal{F}(n_e, m_e, \nu_{eH}, f^0, \omega_e) \end{cases}$$

- If $B = 0 \Rightarrow \sigma_{\perp} = \sigma_{\parallel} = \sigma$

- If $E \sim e^{-i\omega t} \Rightarrow$ dependence of σ on ω

i.e. pulsing via files!

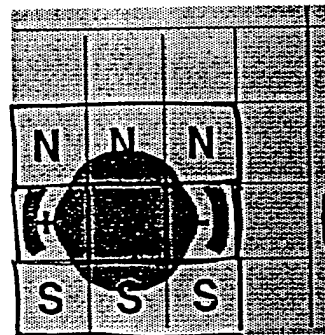
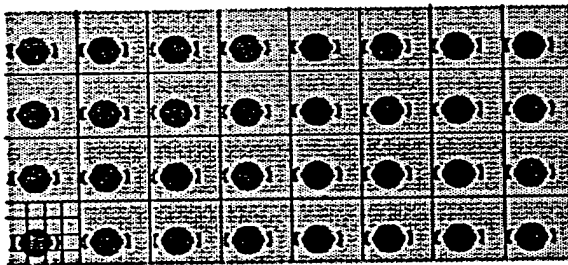
Note: $f^0 = \mathcal{F}(\underline{E_{11}^0}, \underline{E_{\perp}}, \nu_{eH}, T_H, m_e, m_H)$

Lorentz Force: Numerical Modeling

- Governing Equations for \vec{B} and \vec{E}
- Boundary Conditions - The Motz problem

Example 1: Electromagnetic Tiles

Dirichlet: $\vec{F}_\perp \sim \frac{1}{3}\vec{F}_\parallel$; Neumann: $\vec{F}_\perp \sim \vec{F}_\parallel$



Example 2: Alternate stripes of electrodes/magnets $F_H \sim e^{-\frac{\pi}{a}\lambda y}$? penetration

	Dirichlet	Neumann	D-N	Mixed
λ	4	2	8	8
\equiv		\equiv		

Lorentz Force

• MHD Assumptions ($t_c > \omega_p^{-1}$)

- Convection current neglected: $\frac{\rho_c U}{J} \ll 1$
- Force due to net charge neglected: $\frac{\rho_c E}{|J \times B|} \ll 1$

Then:

$$\left\{ \begin{array}{l} \vec{F}_L = \vec{J} \times \vec{B}; \quad E_0 = \text{external} \\ \vec{J} = \sigma(\vec{E} + \vec{u} \times \vec{B}) + \sigma \vec{E}_0 \end{array} \right. \quad \underline{\underline{\text{simple Ohm's law}}}$$

MHD-Control	EMHD-Control
• Apply \vec{B}	• Apply \vec{B} and \vec{E}
• $E = -\nabla\Phi$	• $J \sim \sigma E_0$
• $\nabla^2\Phi = \nabla \cdot (\vec{u} \times \vec{B})$	• $I_{\text{applied}} = \frac{\sigma E_0 B L}{\rho U^2}$
• $I_{\text{induced}} = \frac{\sigma B^2 L}{\rho U}$	

where $R_{em} = \mu\sigma UL \ll 1$ in lab scale (neglect induced fields)

- But Ohm's law for partially ionized gas:

$$\vec{J} + \beta_e \vec{J} \times \vec{b} + s \vec{b} \times (\vec{J} \times \vec{b}) = \sigma(\vec{E} + \vec{u} \times \vec{B}) + \frac{\sigma}{en_e} \nabla p_e$$

↑
"Generalized Ohm's Law"

ion-slip

Discontinuous Galerkin Method - $\mathcal{N}_{\epsilon\kappa T\alpha r}$

- dynamical Direct Numerical Simulation (dDNS)

→ • MHD, Compressible & Incompressible flows

- Full 3D Configurations - Arbitrary Geometric Complexity

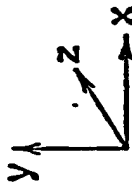
→ • Unstructured/Hybrids Grids

→ • High-Order/Spectral Accuracy

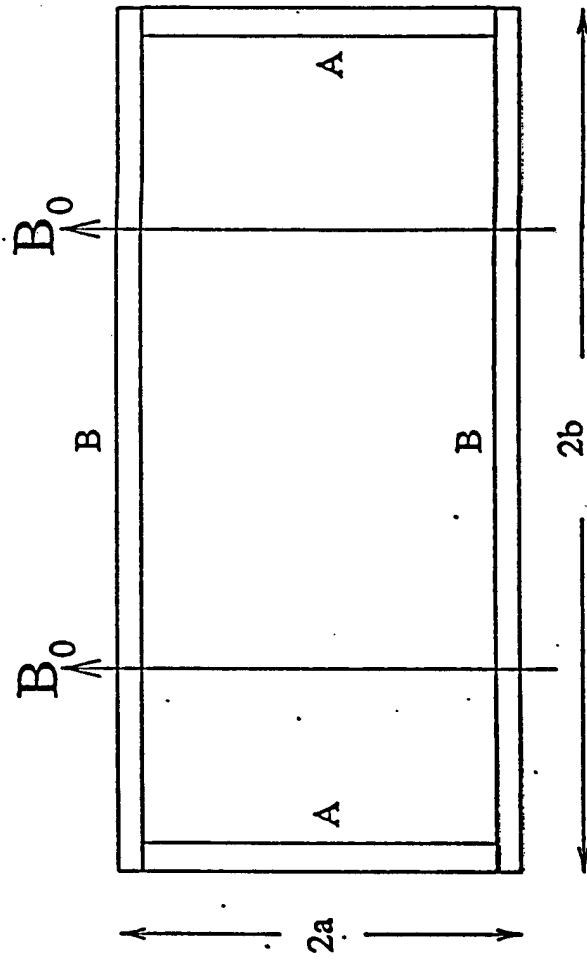
- Conservative Formulation
- h-refinement for shocks/discontinuities
- ALE Algorithm for Moving Rotating Subdomains
- METIS/MPI-based Parallelization

\therefore Convergence of $(FV + FE + Spectral)$
 $\rightarrow \underline{DG}$
 \sim

• MACH 2/3 prototype - but high-order...



Hartmann-Hunt Flow : 3D



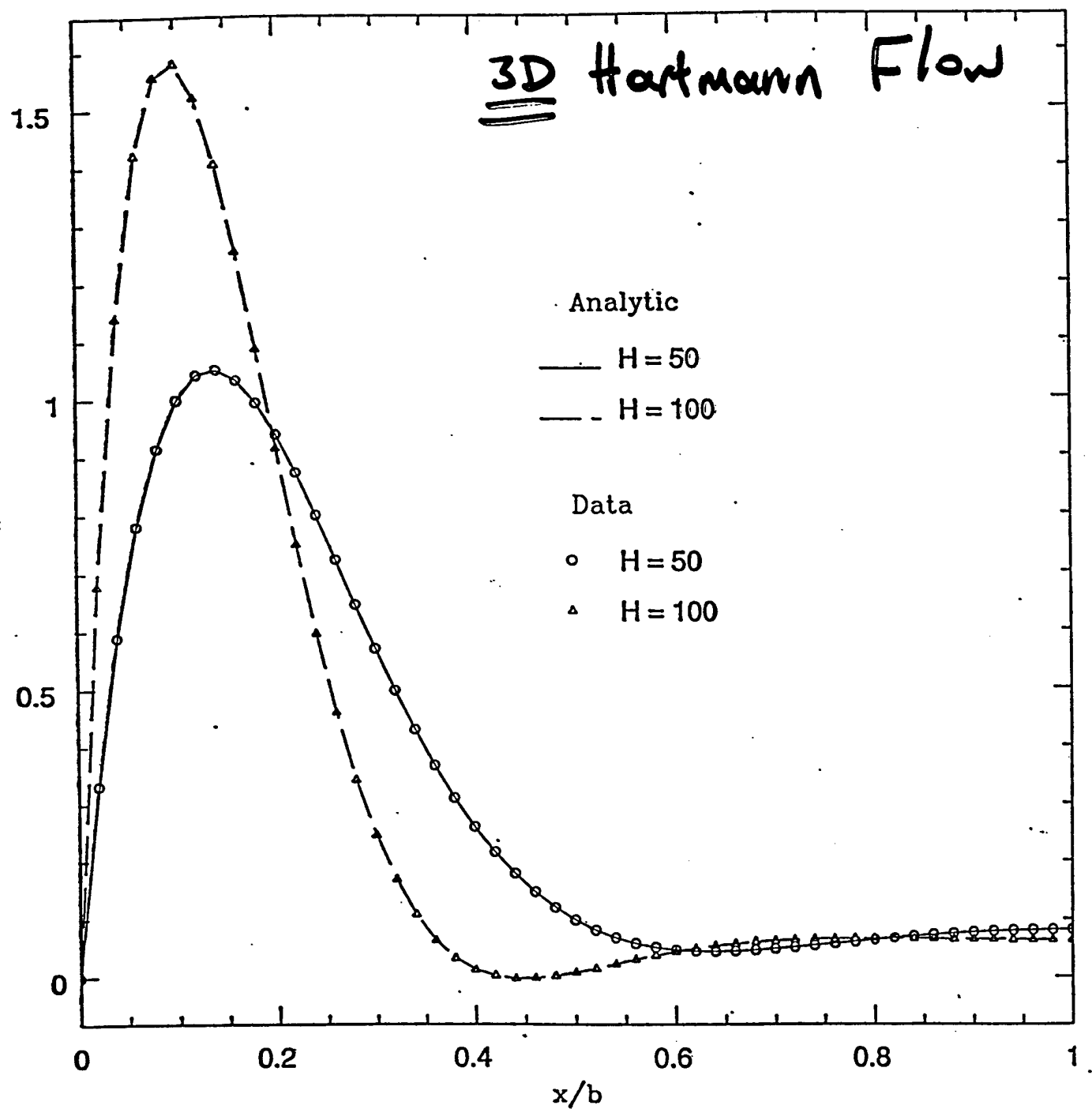
AA: Perfect Insulators

BB: Perfect Conductors

Flow is into the page

$Re = 100, Re_{mag} = 1, N = 9$

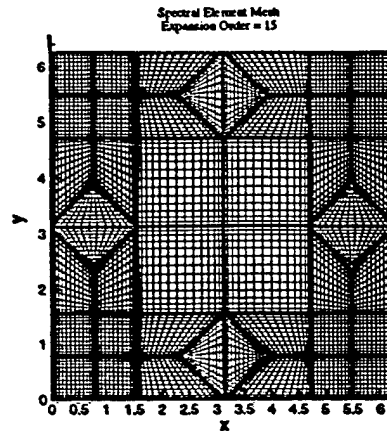
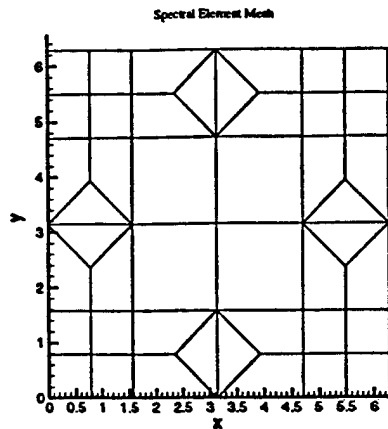
3D Hartmann Flow



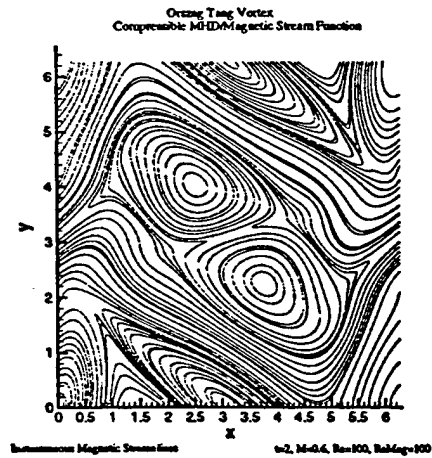
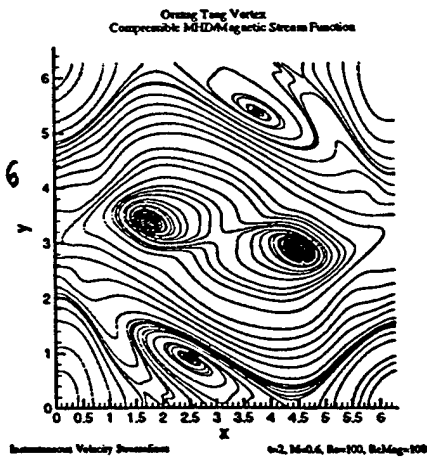
* Spectral/hp on Unstructured Grids.
(AFOSR)

Orszag-Tang MHD-Vortex

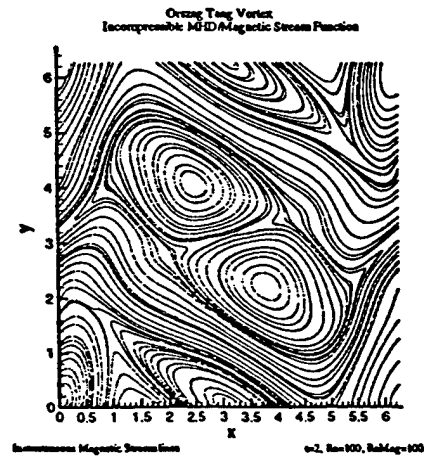
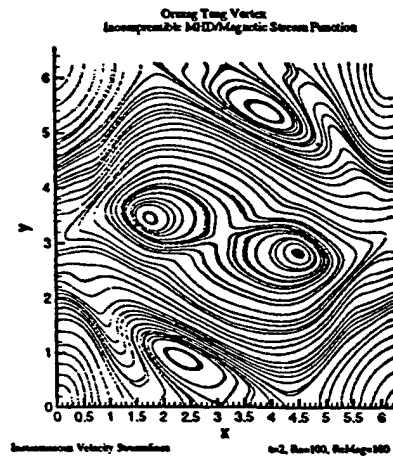
Hybrid
Grid



$M=0.6$



$M=0$



H-P Adaptive Refinement: Viscous Supersonic Flows

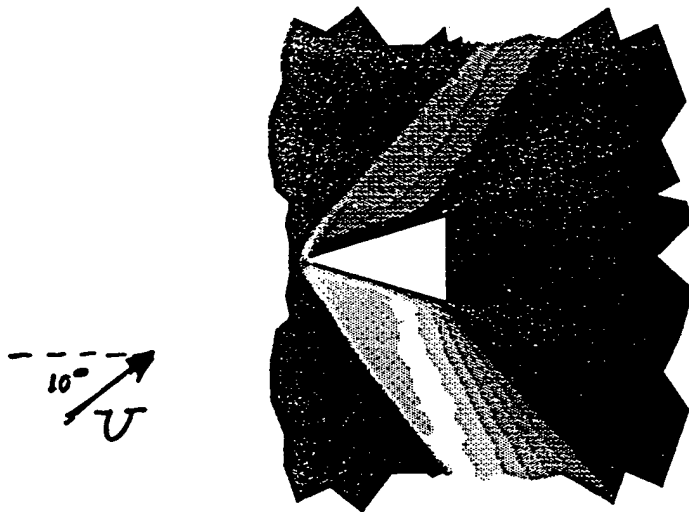


Figure 1: Discontinuous Galerkin Simulation: Density contours

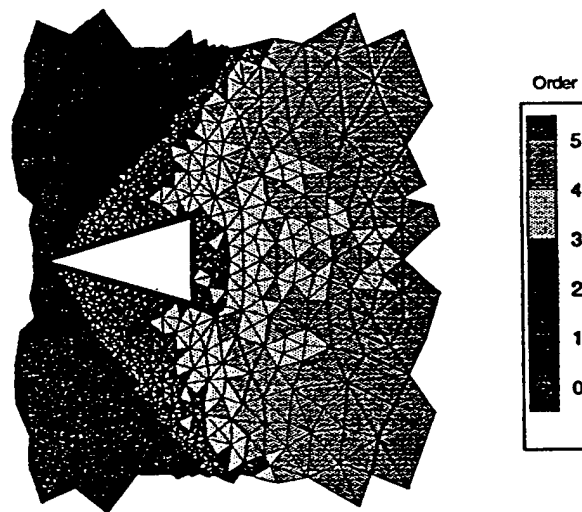
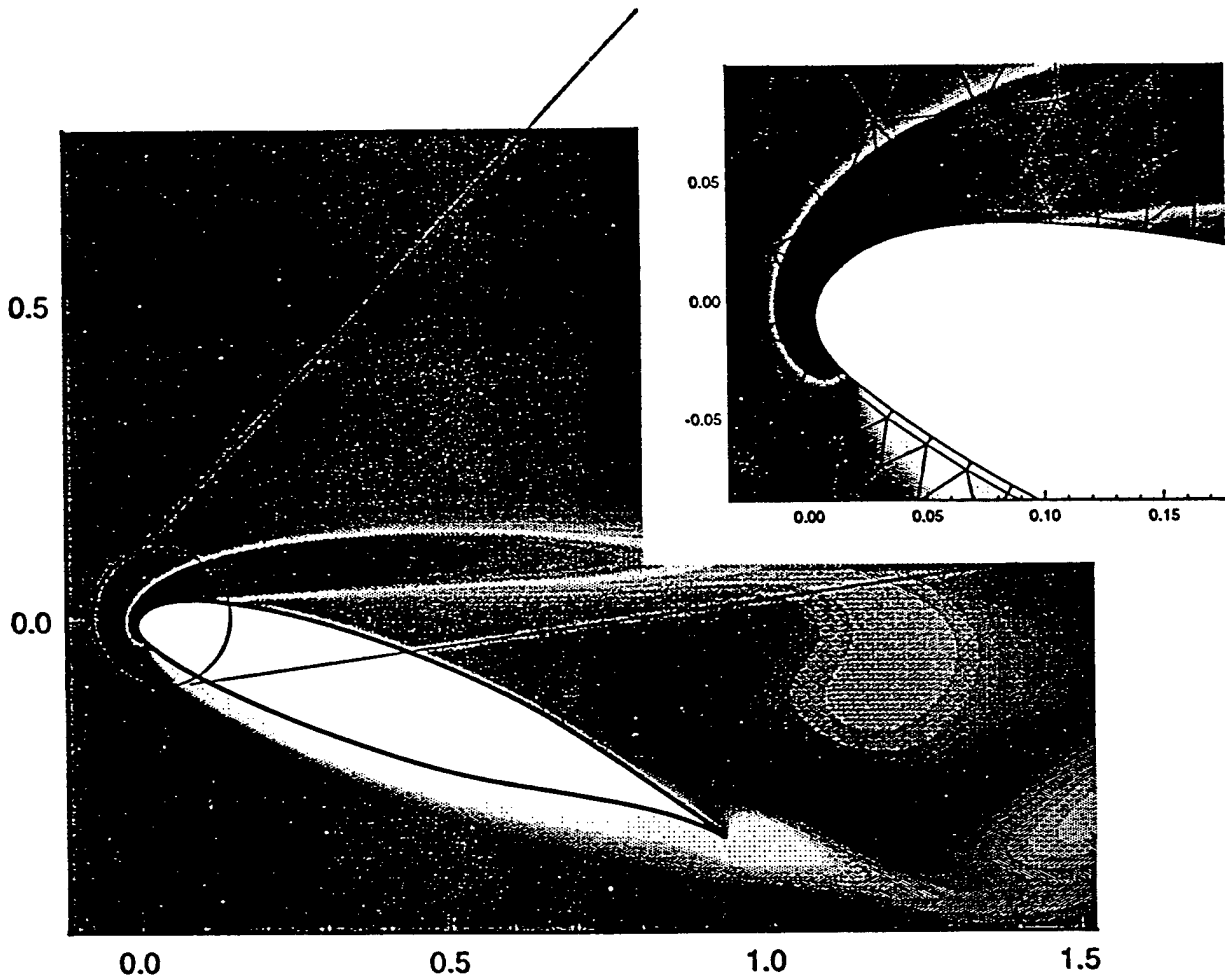


Figure 2: Unstructured grid and variable-order per element

• HYBRID APPROACH:

- DNS - near wall / structured
- LES in equilibrium regions

Hybrid-Element Boundary Layer Resolution



PhD Thesis: T. Warburton

Plan: { • DNS with h-p refinement.

{ • LES in equilibrium with h-p refinement

→ high Re. #, Complex Geometry

MHD/EMHD-Simulations

I. Laminar & Turbulent Wakes

- - vortex street suppression
- phase/frequency control

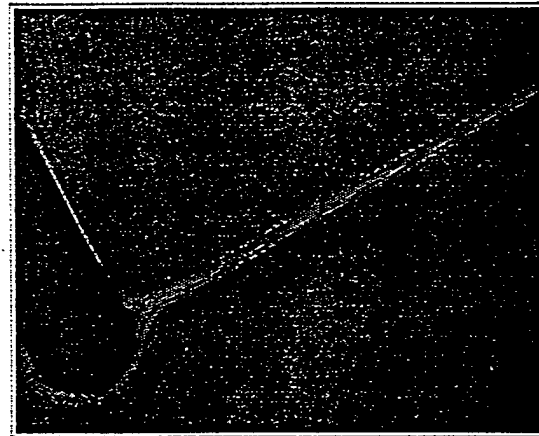
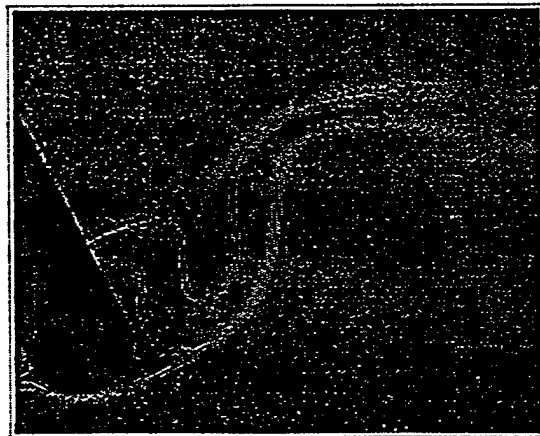
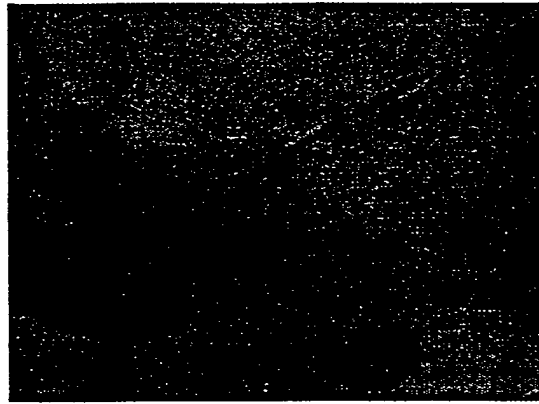
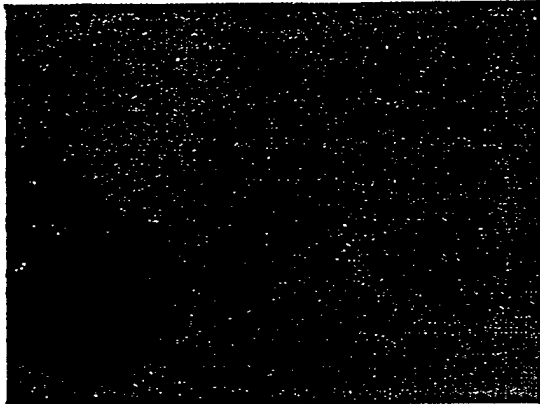
II. Wall Turbulence

- High σ , spanwise forcing/MHD
- Low σ , streamwise forcing
- - Low σ , "normal" forcing

Method: Parallel DNS - The $\mathcal{N}\epsilon\kappa\mathcal{T}\alpha r$ Code

Experiments: Conflicting results

EMHD control of the flow around a circular cylinder

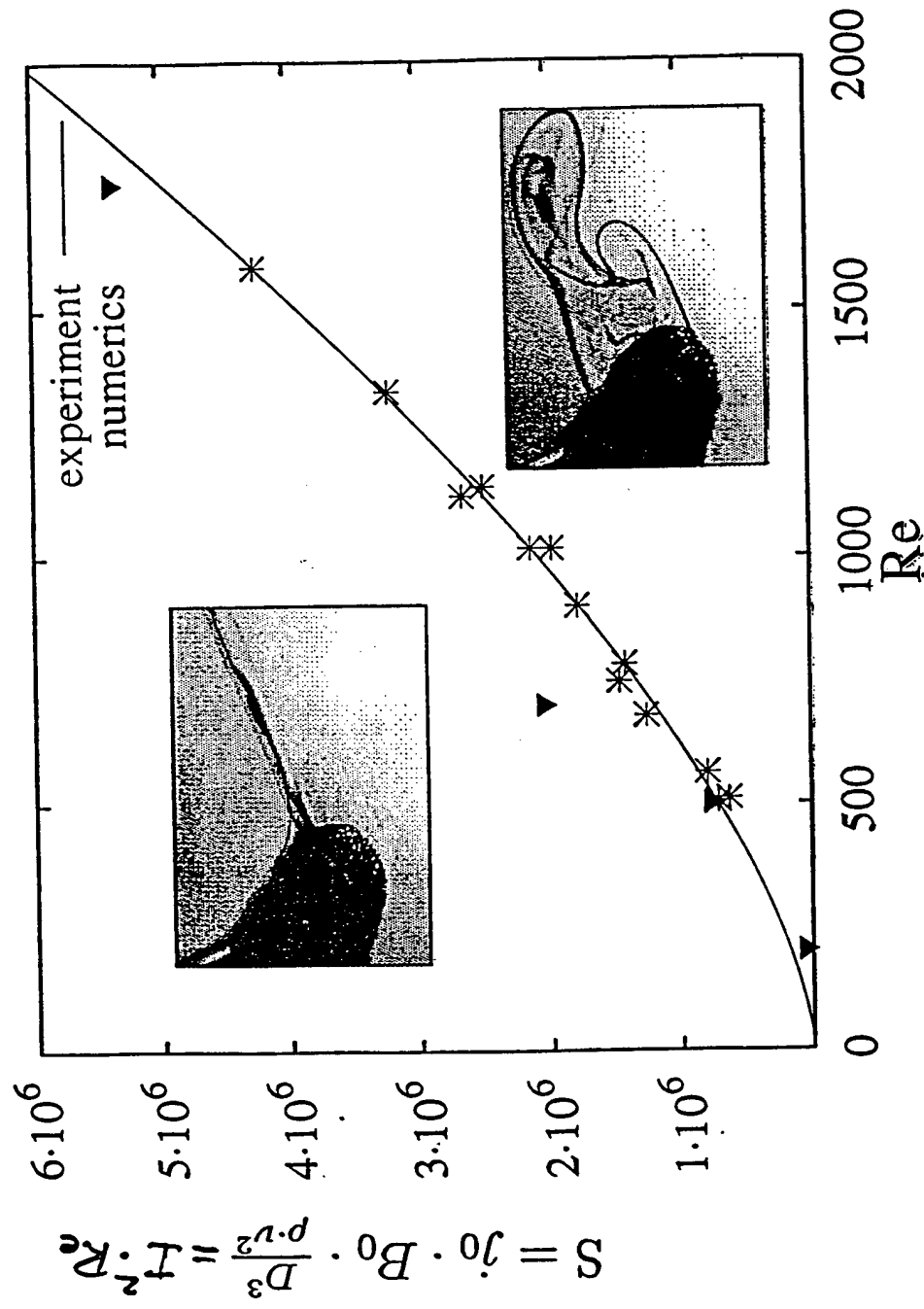


Dimensionless numbers:

$$Re = \frac{v_{\infty} d}{\nu} \quad - \text{Reynolds number}$$

$$N = \frac{j_0 B_0 d}{\rho v_{\infty}^2} \quad - \text{Interaction Parameter}$$

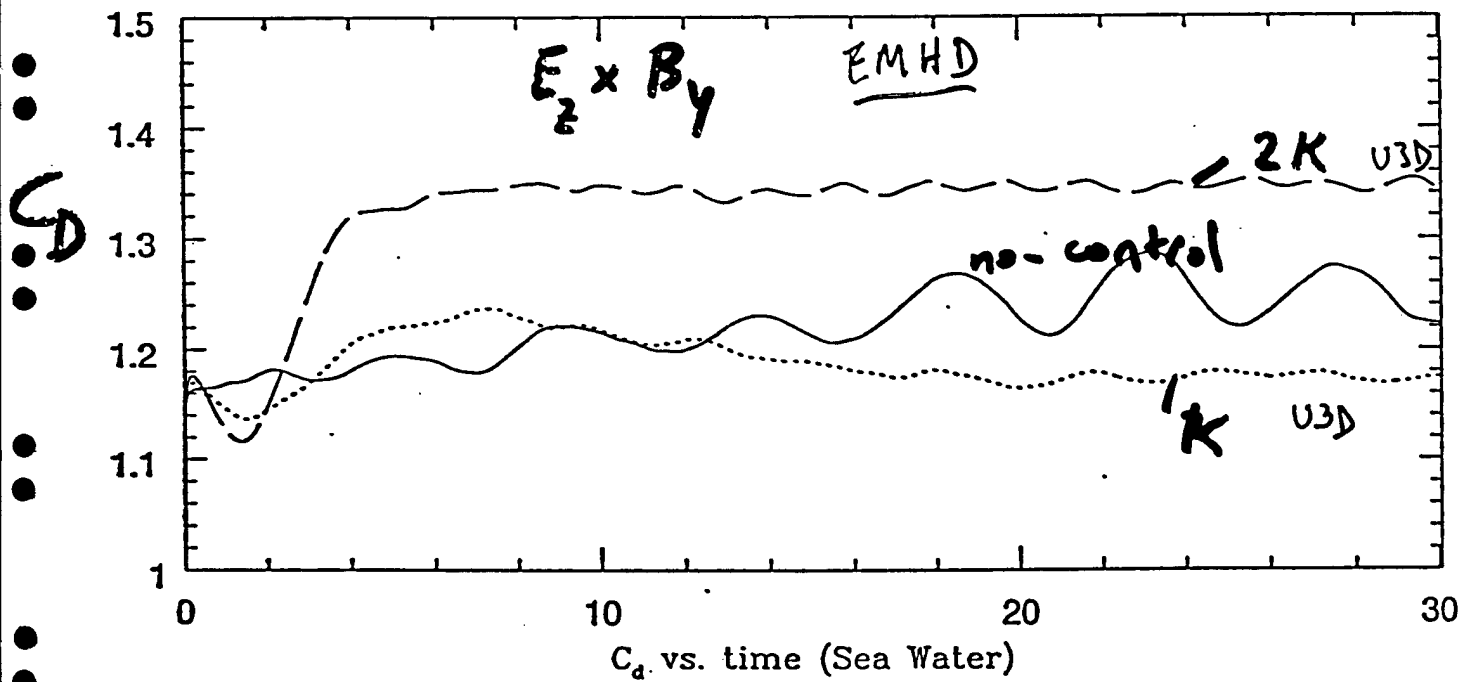
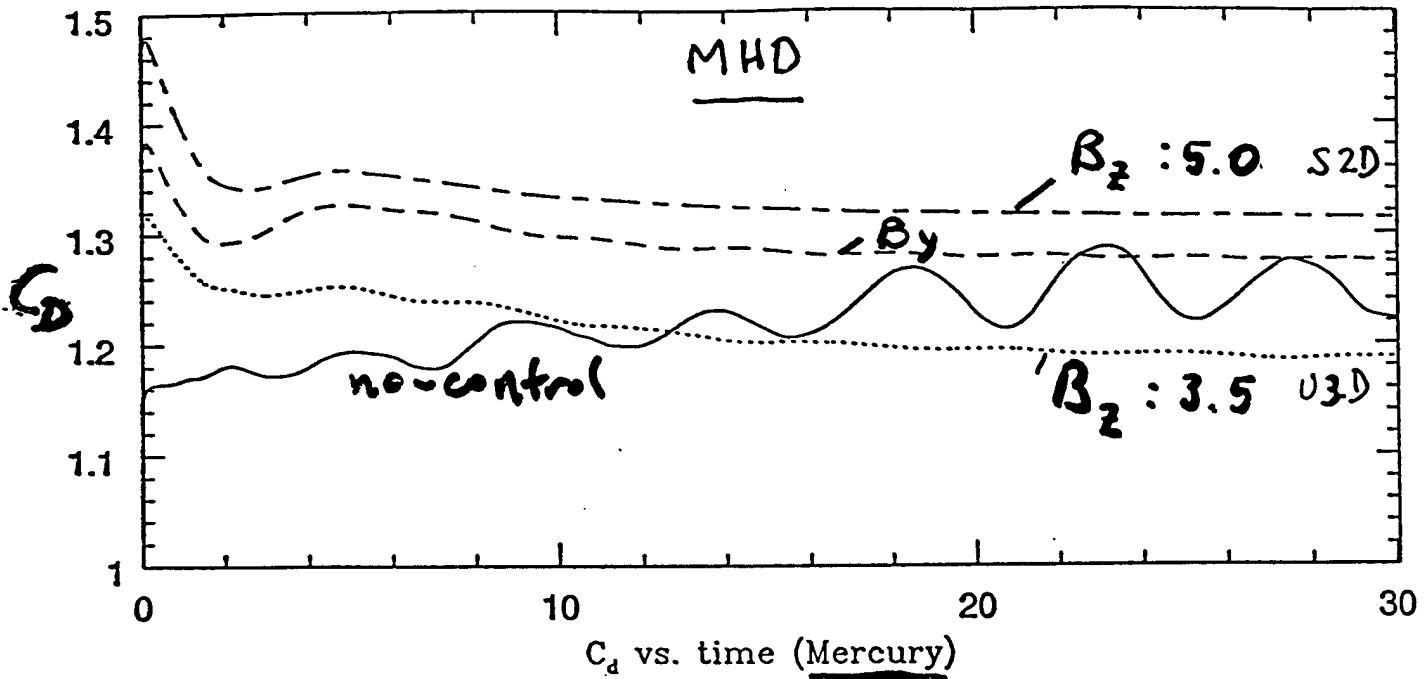
Suppression of the Kármán vortex street



TURBULENT WAKES

AIAA-95

Cylinder, $Re = 500$



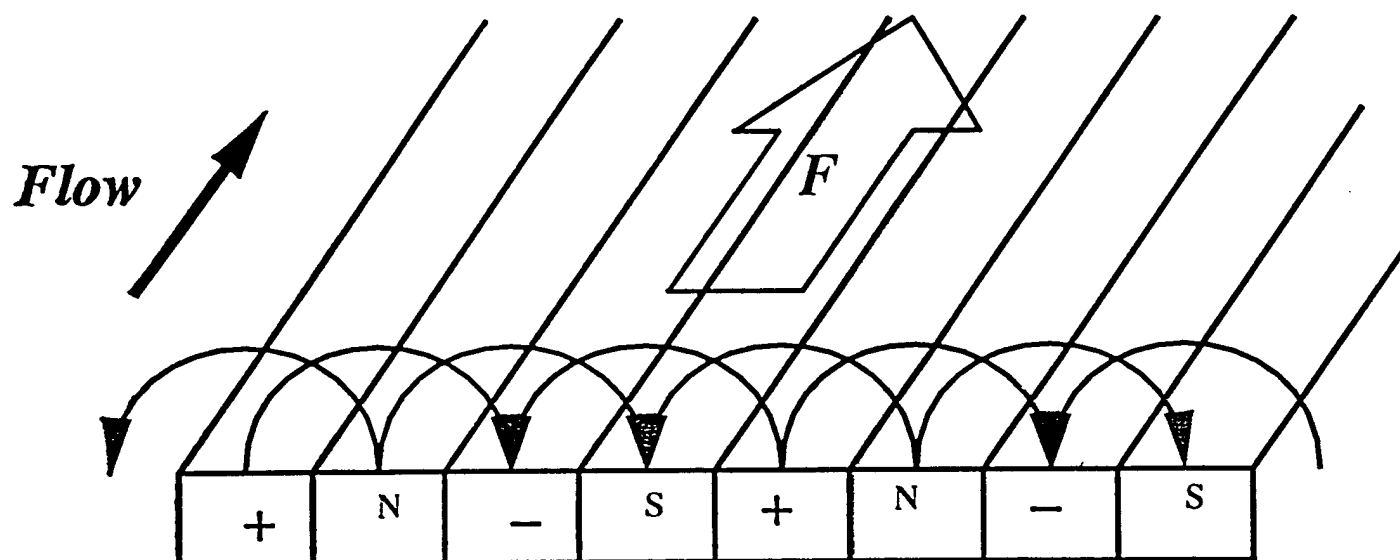
\therefore Changes are non-Monotonic!

Active Control: Lorentz Body Force

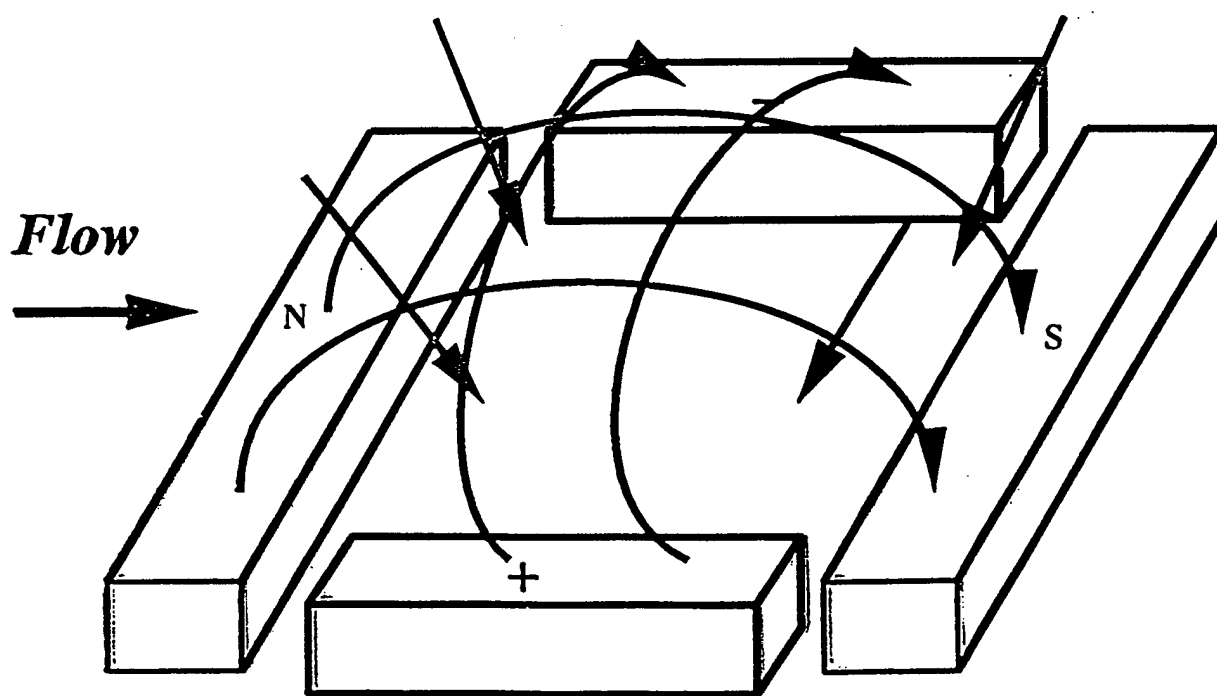
Ph.D.: S
Crawford
Y. du

—▶ Electric Field
—▶ Magnetic Field
—▶ Lorentz Force

* DOE
* AFOSR

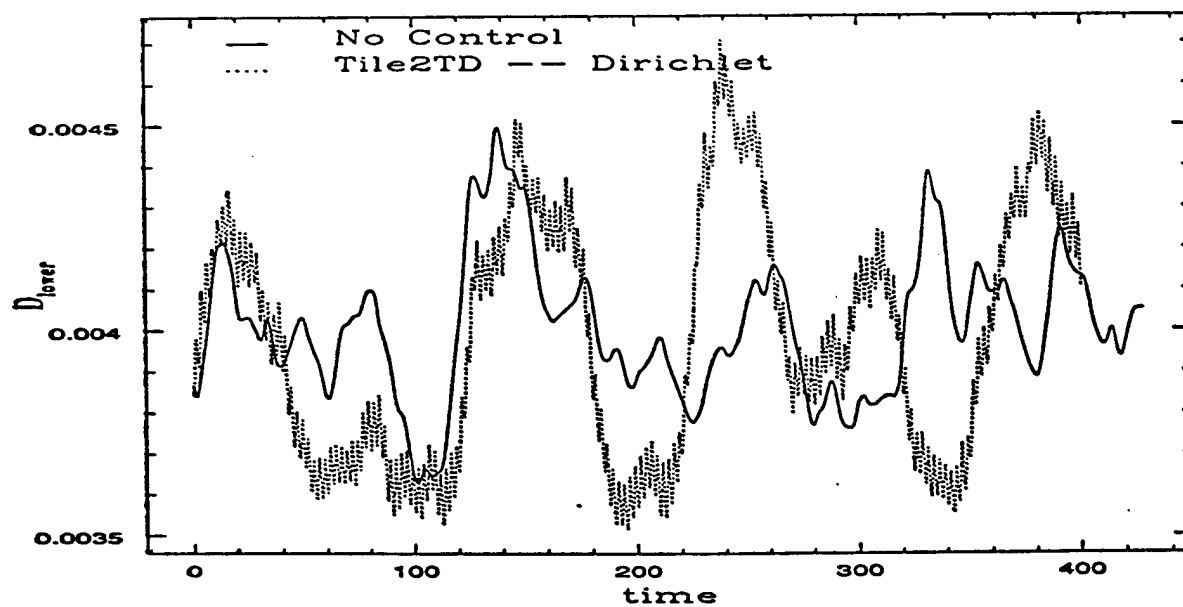
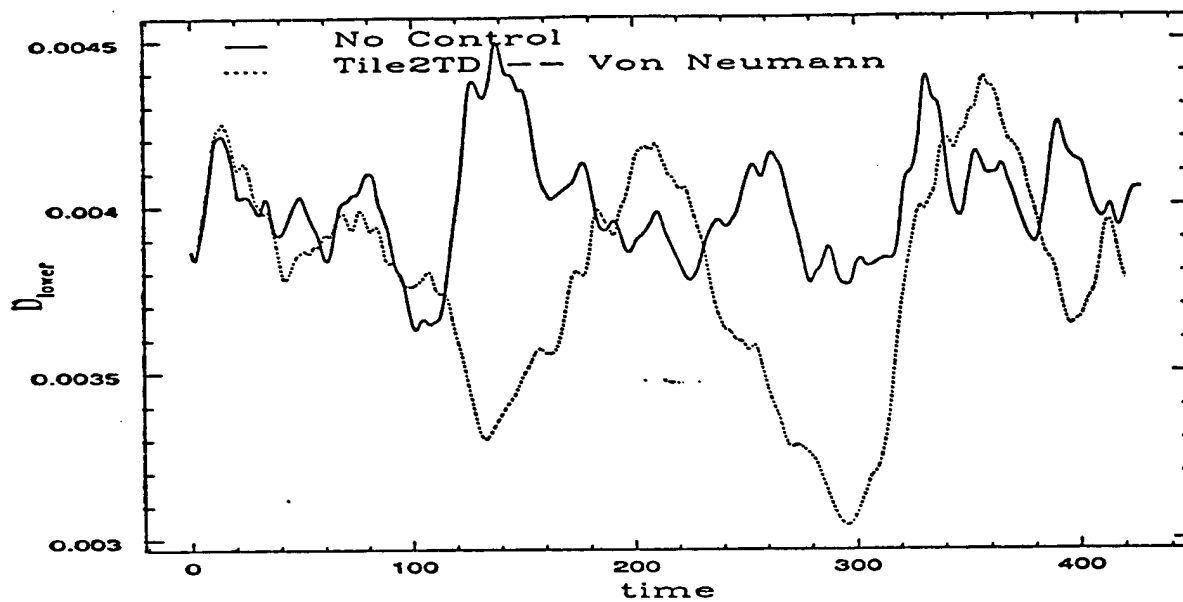


Henoch & Stace, 1995



Nosenchuck & Brown, 1994

EMHD: Shear Stress History – Effects of BC



NEAR-WALL TURBULENCE and LAMB VECTOR

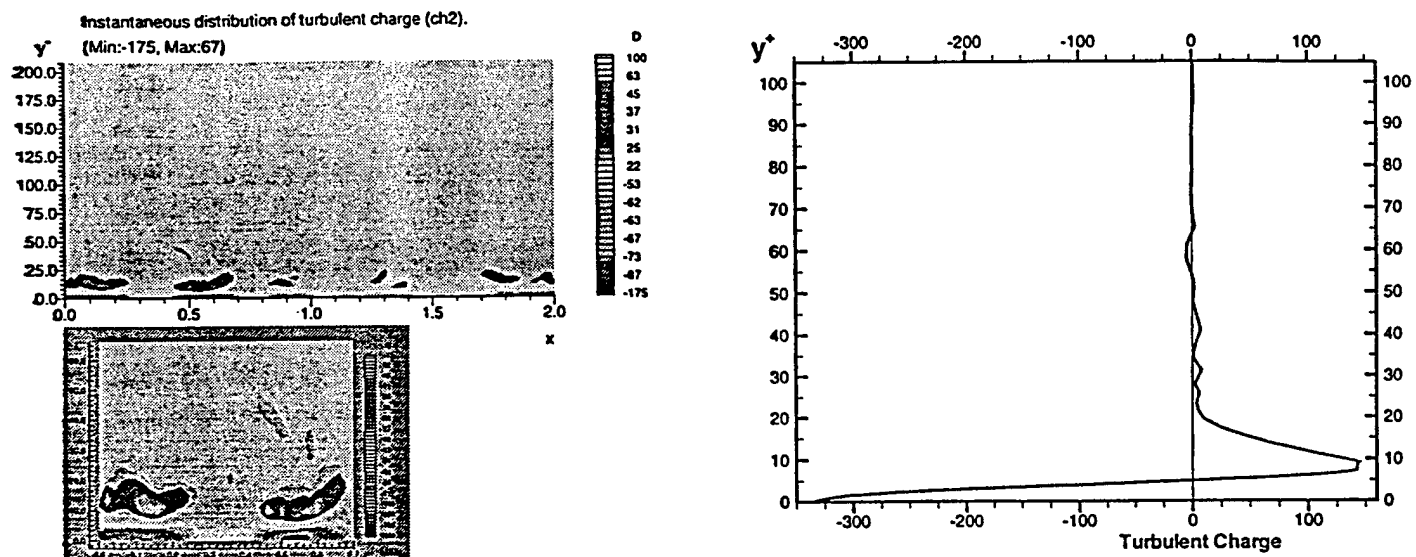


Figure 1: Dipole structure of the divergence of the Lamb vector: turbulent charge

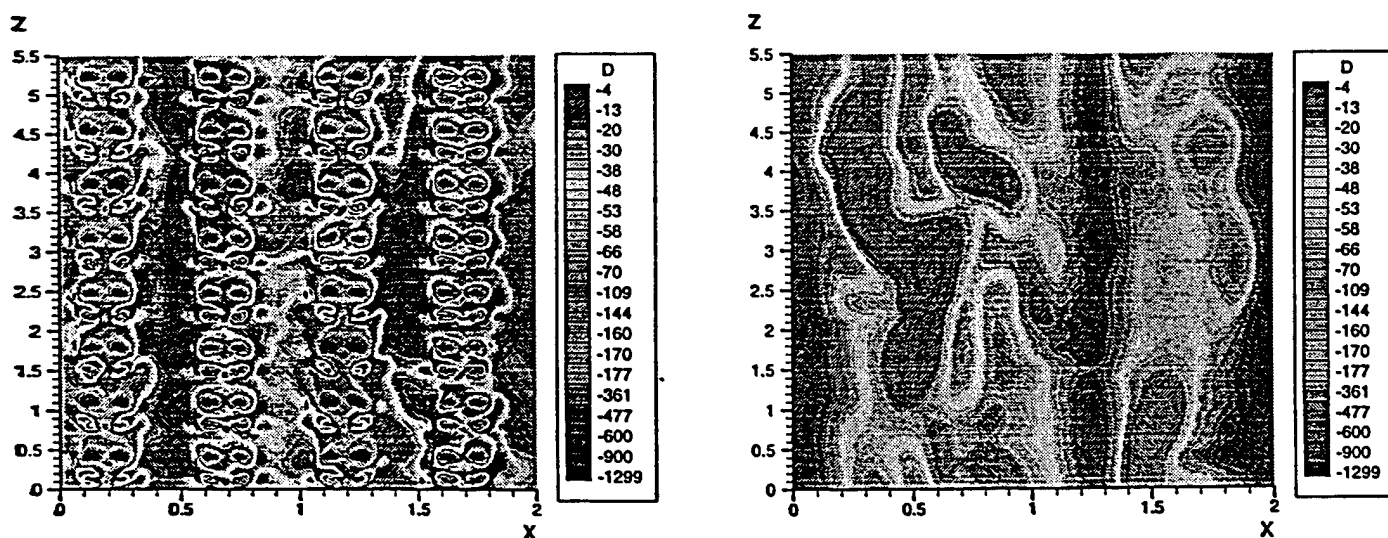


Figure 2: Footprint of the turbulent charge: LEFT - EMHD on; RIGHT: EMHD off

Summary

- Explore MHD, EMHD and EHD
- Strong electrical conductivity non-uniformity
- Selection of physical model is application-dependent
 - degree of ionization
- Transitional Flow - No *ad hoc* models
- Numerical Model ($\mathcal{N}\epsilon\kappa\mathcal{T}\alpha r$):
 - High order
 - Hybrid grids
- Benchmark Experiments

2D vortex dynamics associated with shock splitting

Kremeyer, Nazarenko, Newell (Arizona).

Is observed shock splitting due
largely to plasma electromagnetics
or due solely to gas heating
which accompany the introduction
of non-equilibrium plasmas into a
gas flow?

Shock wave attenuation in argon plasmas

Ganguly, Bletzinger & Garscadden 1997

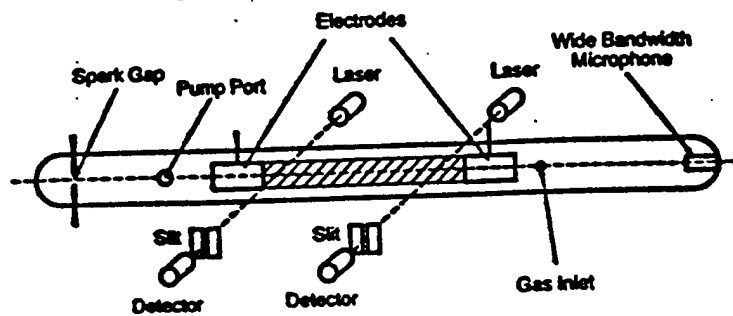


Fig. 1. Schematic of the experimental set-up.

- Shock attenuation & acceleration
1D effects VT.
- Shock splitting. ???
- Ionisation unimportant, $\alpha \ll 1$?

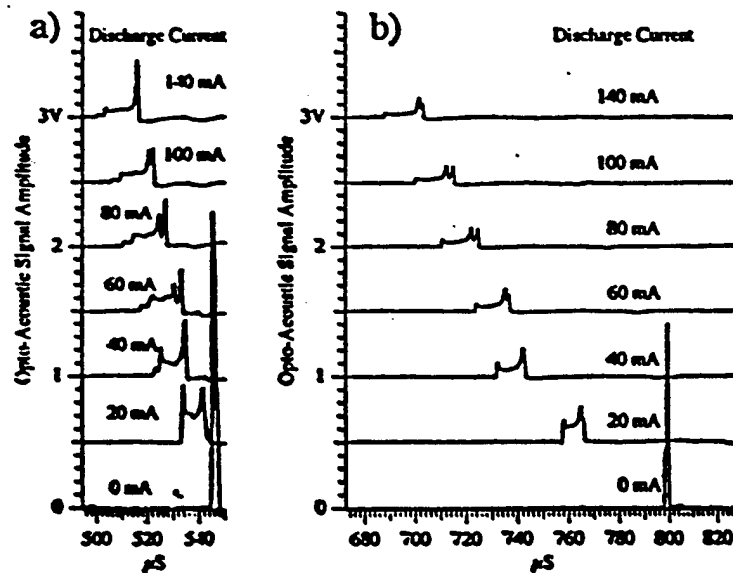
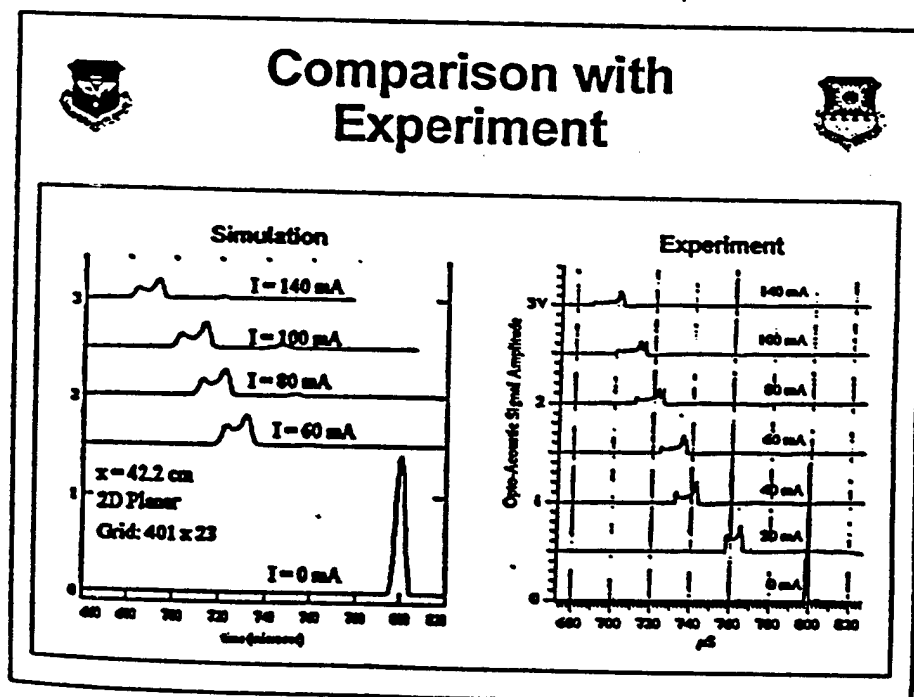
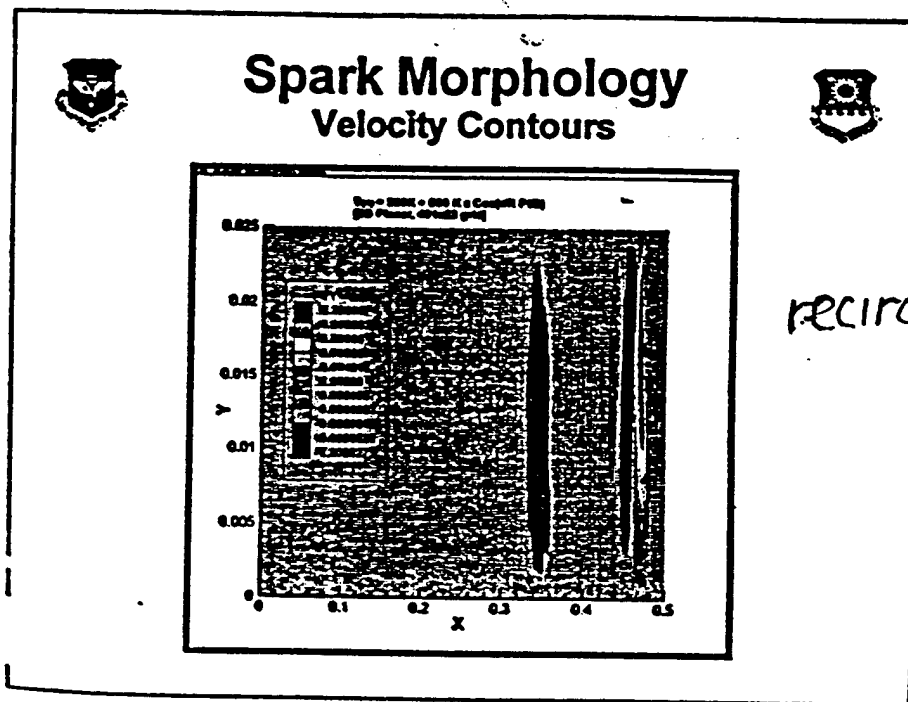


Fig. 2. Shock induced opto-acoustic signals in a 30 Torr argon discharge. (a) 30.2 cm from the spark source, (b) 42.2 cm from the spark source.

2D effects.

CFD of thermal effects, Bailey & Hilburn '1997



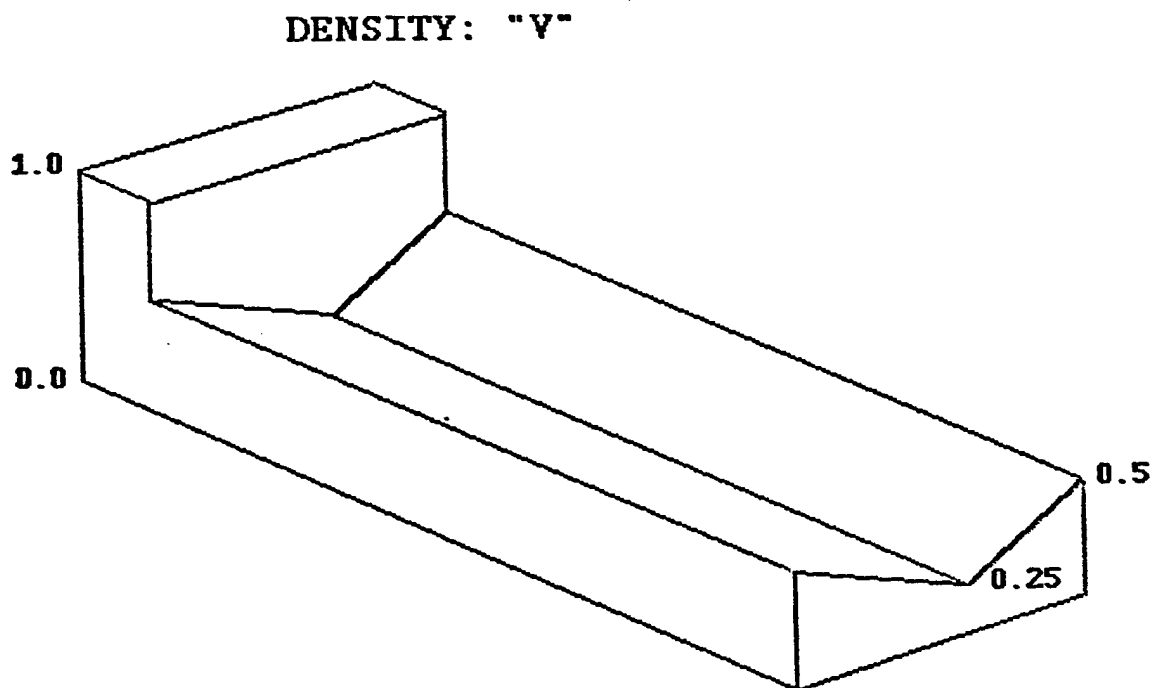
2D Shock Tube Simulation

Left Boundary: $p = 1.0$; $d = 1.0$; $u = v = 0$

Right Boundary: $p = 0.1$; $d = "V"$; $u = v = 0$

(top and bottom B.C's are "reflecting slip")

Initially, these two states
meet at a discontinuity.

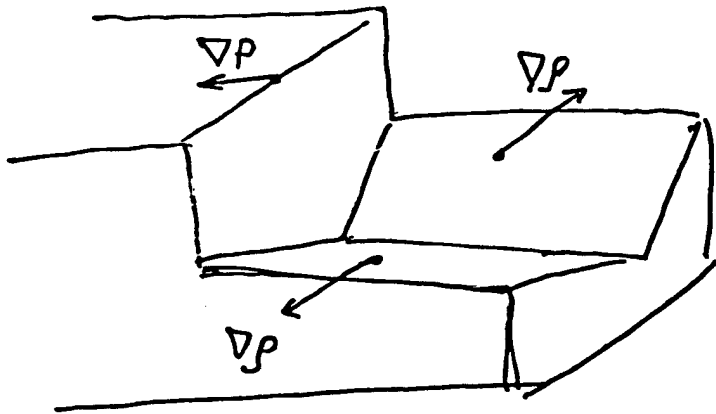


Baroclinic Vorticity Generation

$$\underline{\omega} = \nabla \times \underline{u} \quad \text{vorticity}$$

$$\left[\partial_t + (\underline{u} \cdot \nabla) \right] \underline{\omega} - (\underline{\omega} \cdot \nabla) \underline{u} = - \underline{\omega} \nabla \cdot \underline{u} - \underline{\nabla \frac{1}{\rho} \times \nabla p}$$

baroclinic
term



Potential Vorticity Conservation

2D Barotropic ($p = p(\rho)$) fluid

$$\left[\partial_t + (\underline{u} \cdot \nabla) \right] \frac{\underline{\omega}}{\rho} = 0$$

Potential vorticity $\frac{\underline{\omega}}{\rho}$ is conserved by each fluid element.

SIMULATION METHOD:

(of the 2D Euler equations)

PHYSICAL ASPECT RATIO ($x:y$) = 100:1

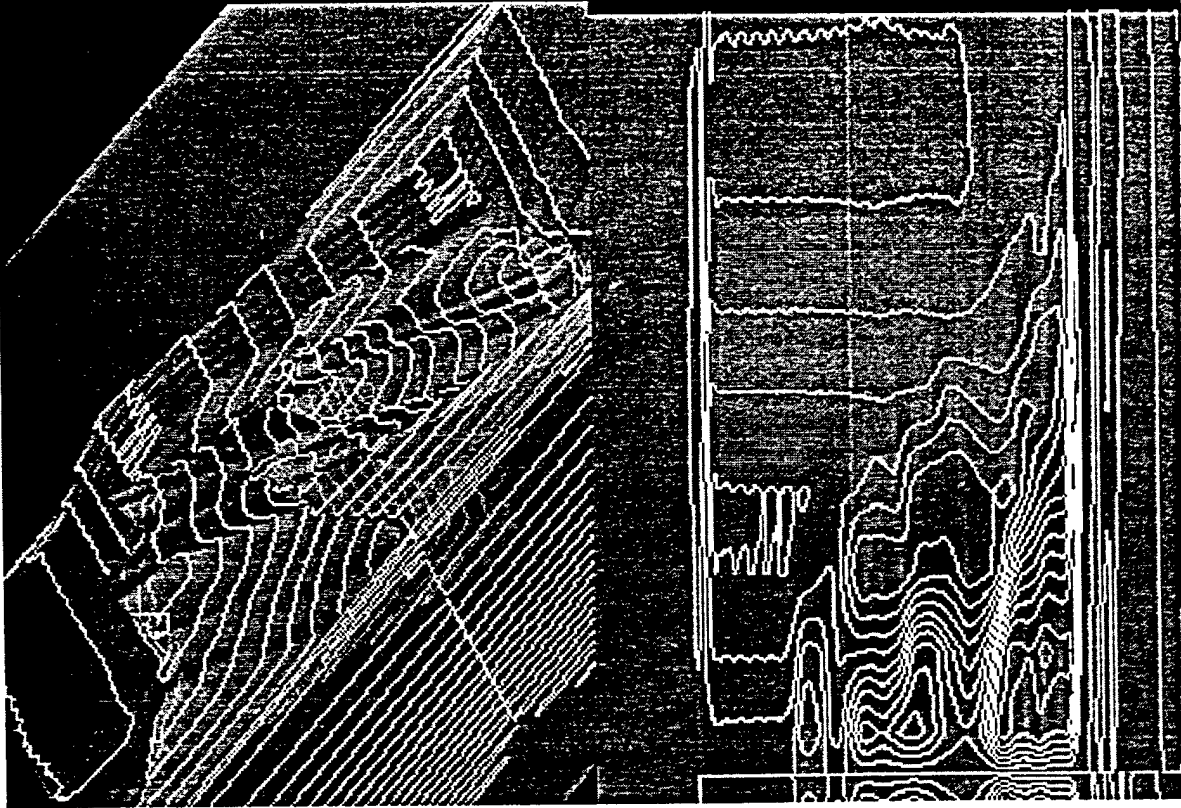
of gridpoints in x direction = 400

of gridpoints in y direction = 20

of ghostpoints = 3 (on each side)

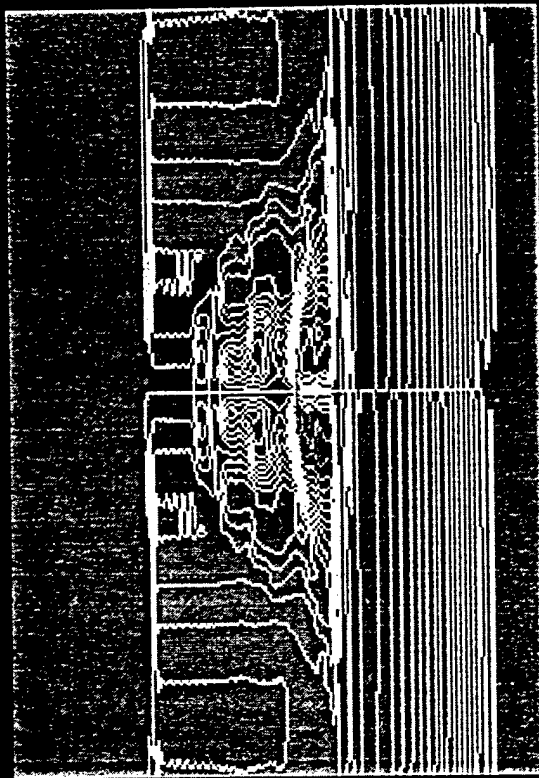
- 1: Given the fluid parameters at each gridpoint, find the eigenvectors to Roe's matrices.
- 2: Use a 5th order weighted ENO scheme to find the flux eigenvectors at half gridpoints.
- 3: Use a 3rd order Runge Kutta routine to propagate the half gridpoint fluxes and find the new fluid parameters at the real gridpoints.
- 4: Repeat.

(1) Vorticity Landscape



(3) = half
of (2)

(2) Vorticity Contours



← front
jump

← back
jump

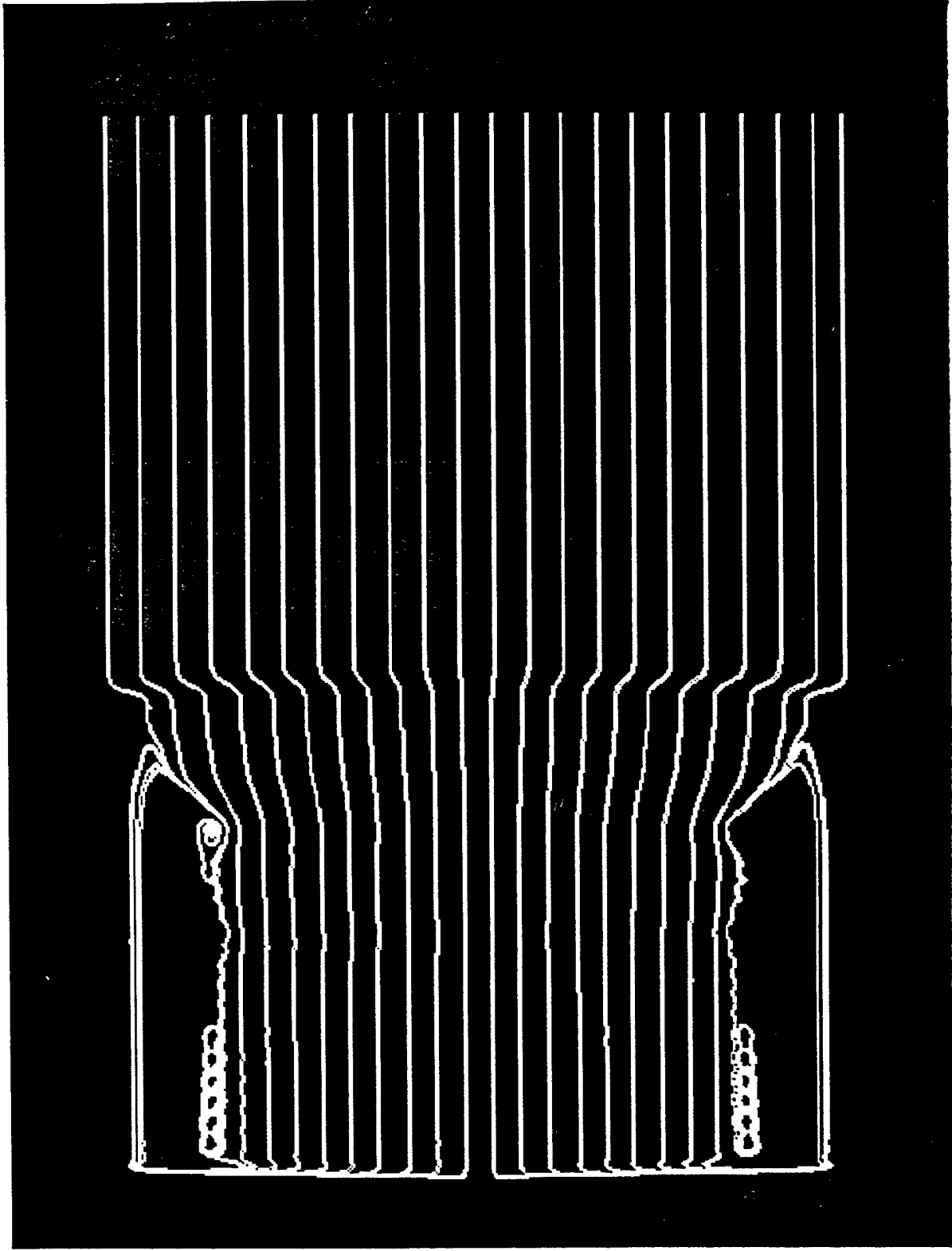
(4):

$$\frac{\partial}{\partial x} \int \rho dy$$

Same
scale as
in (3).

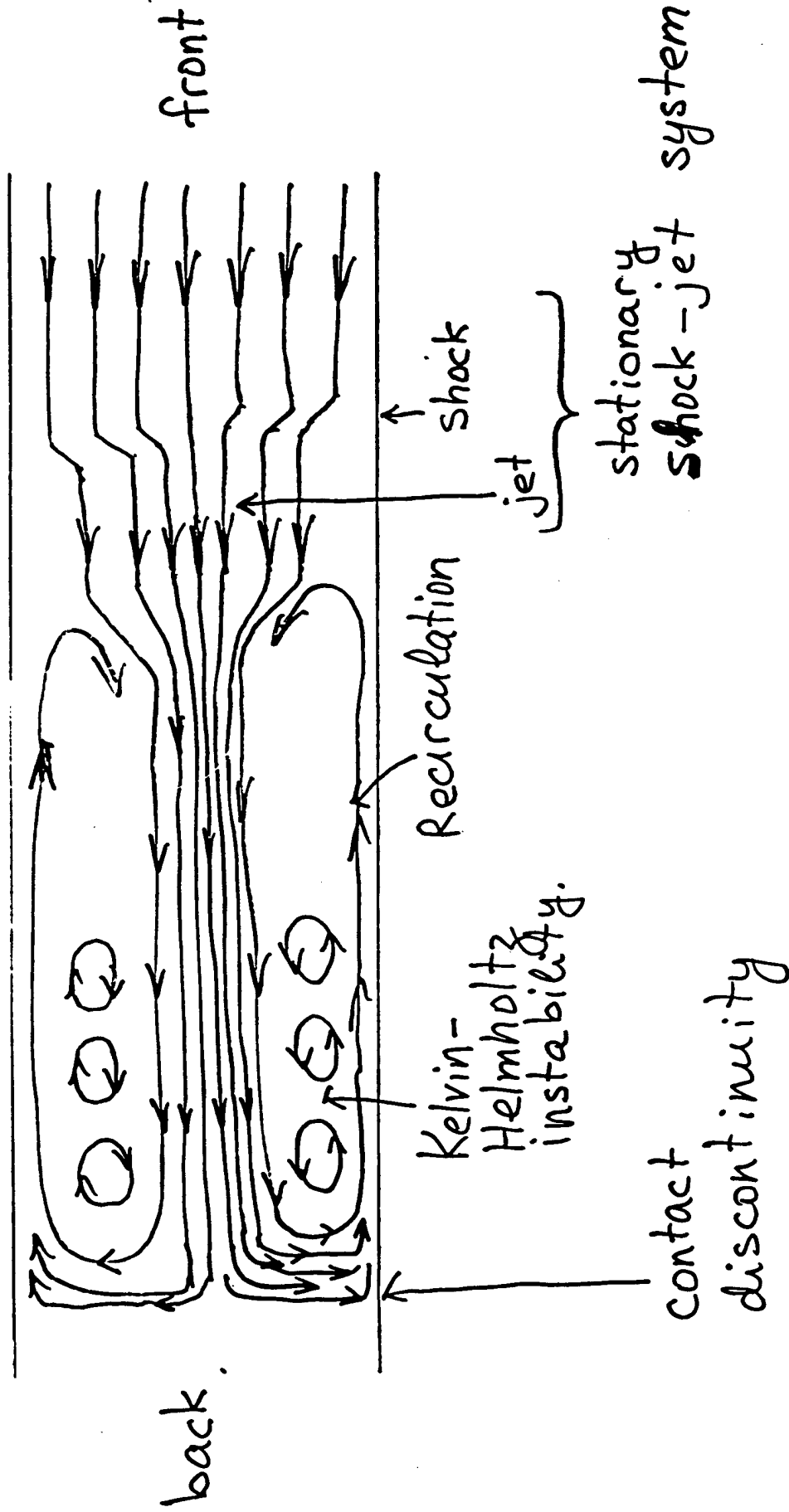


Streamlines

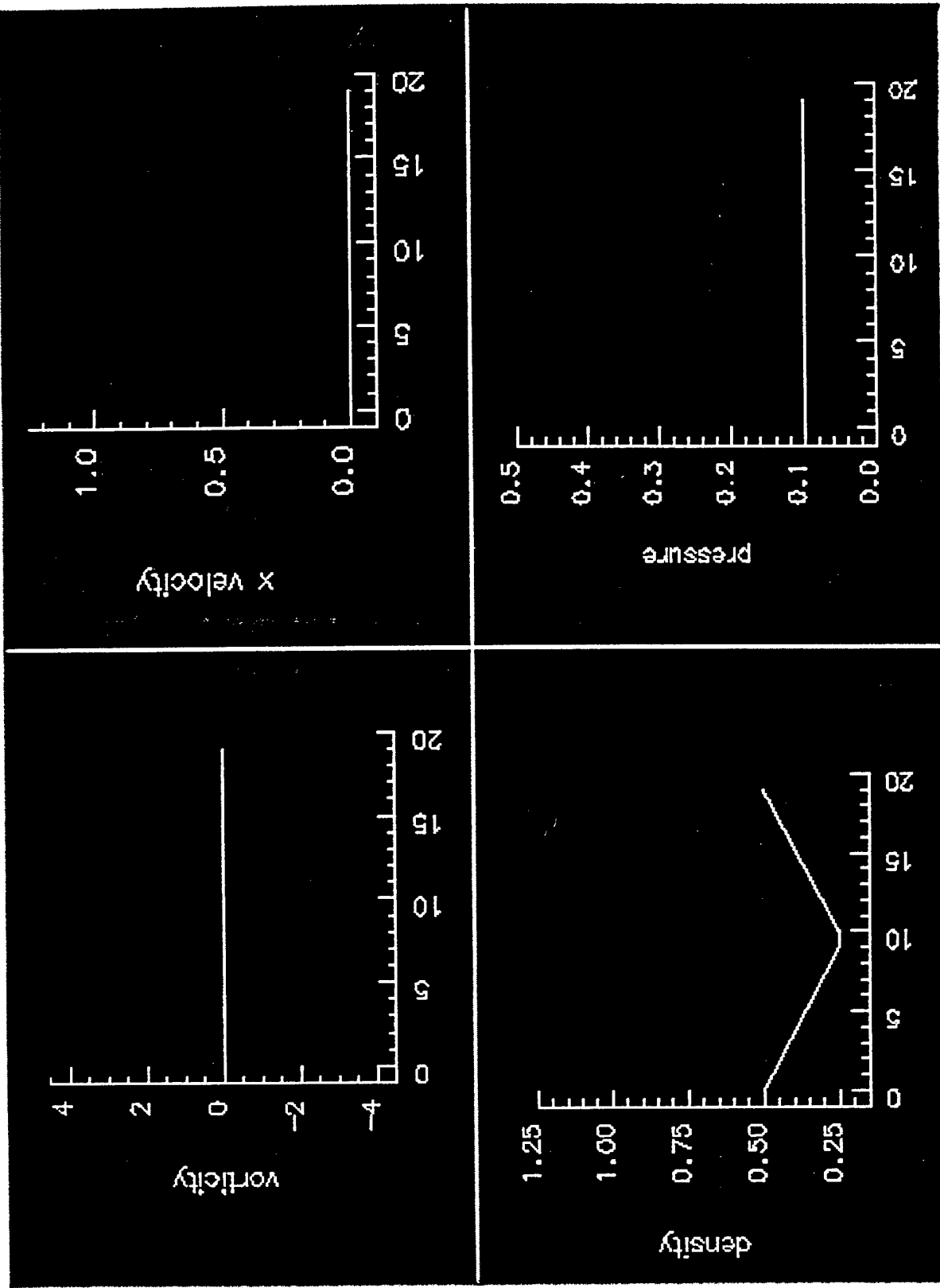


↑ back ↑ front

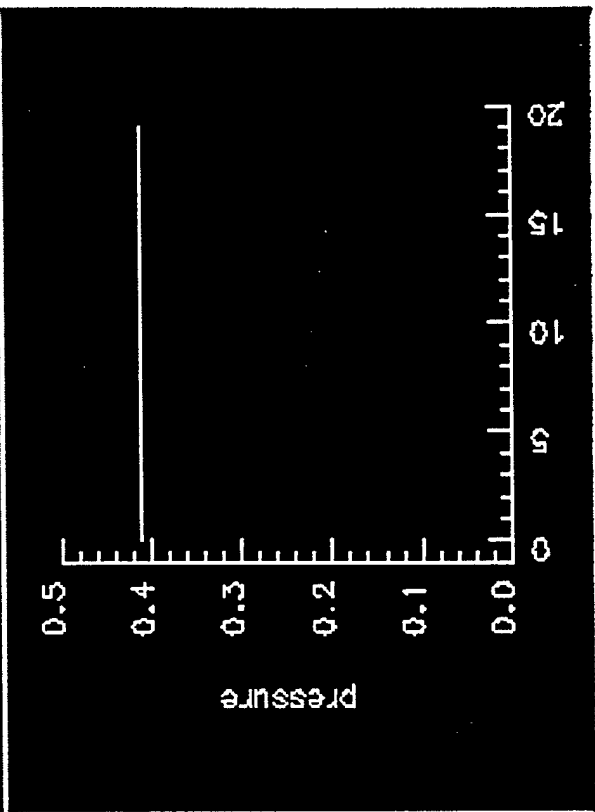
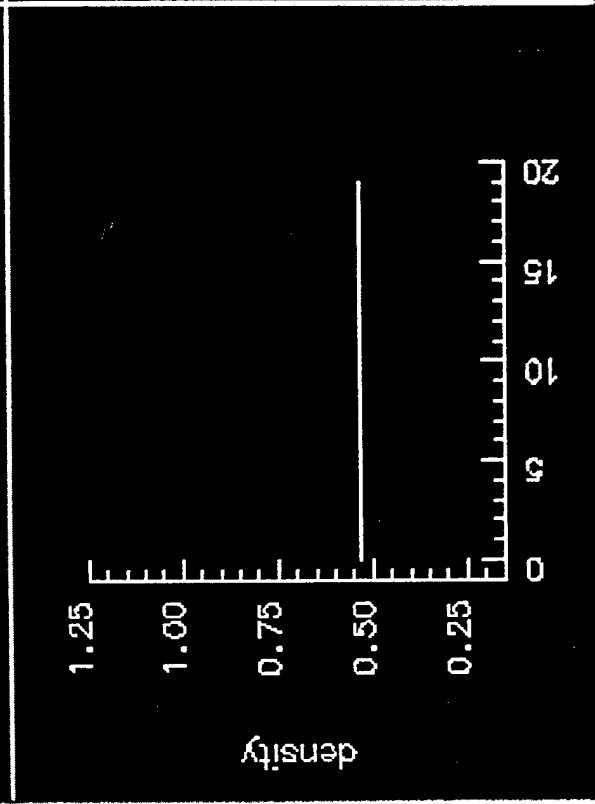
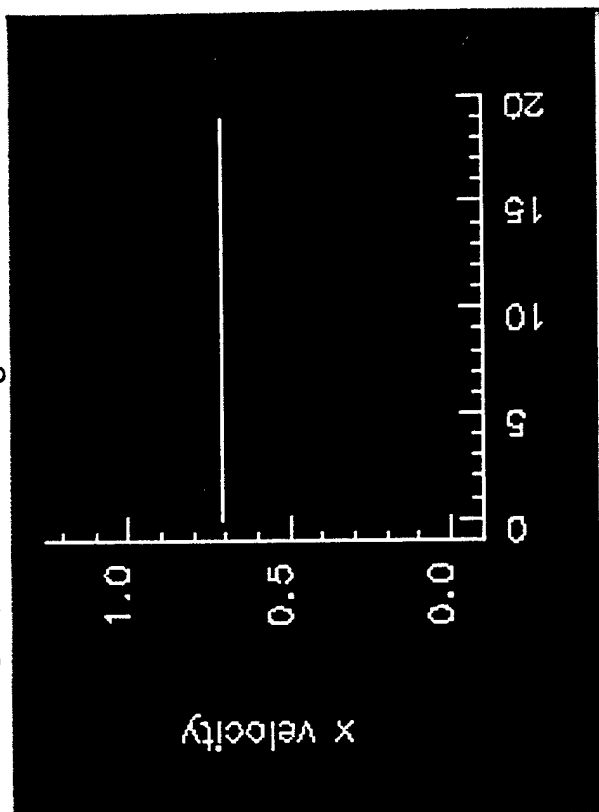
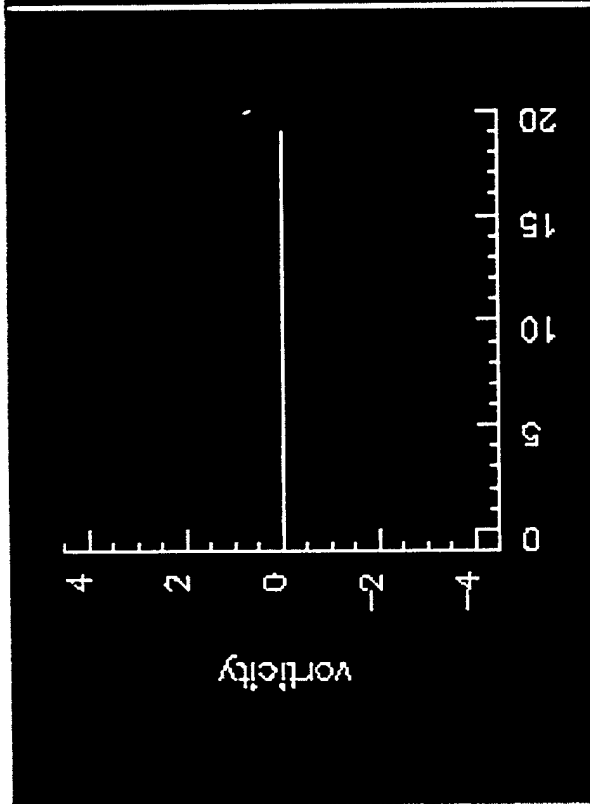
Flow Structure



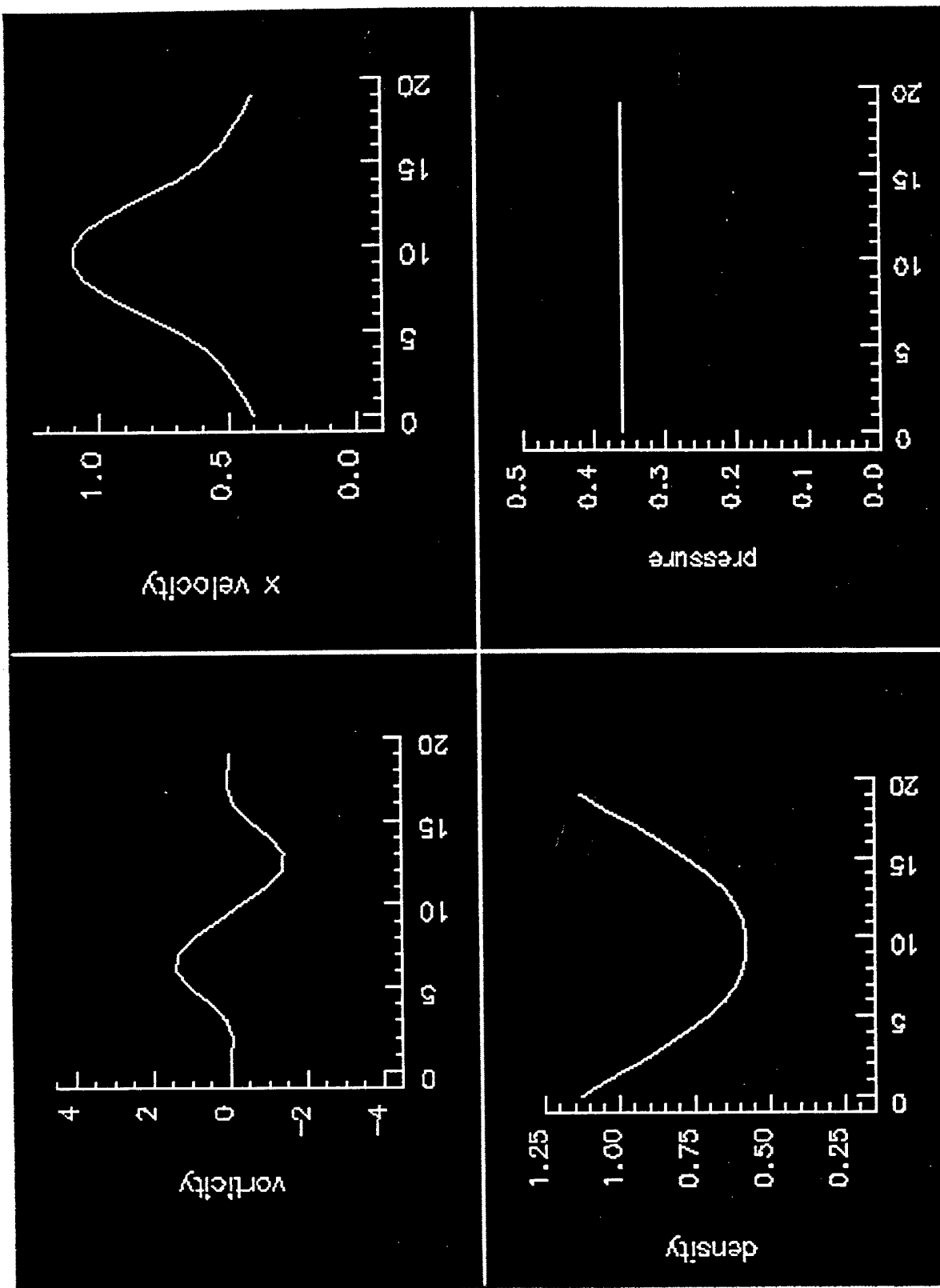
Profiles in front of the Shock



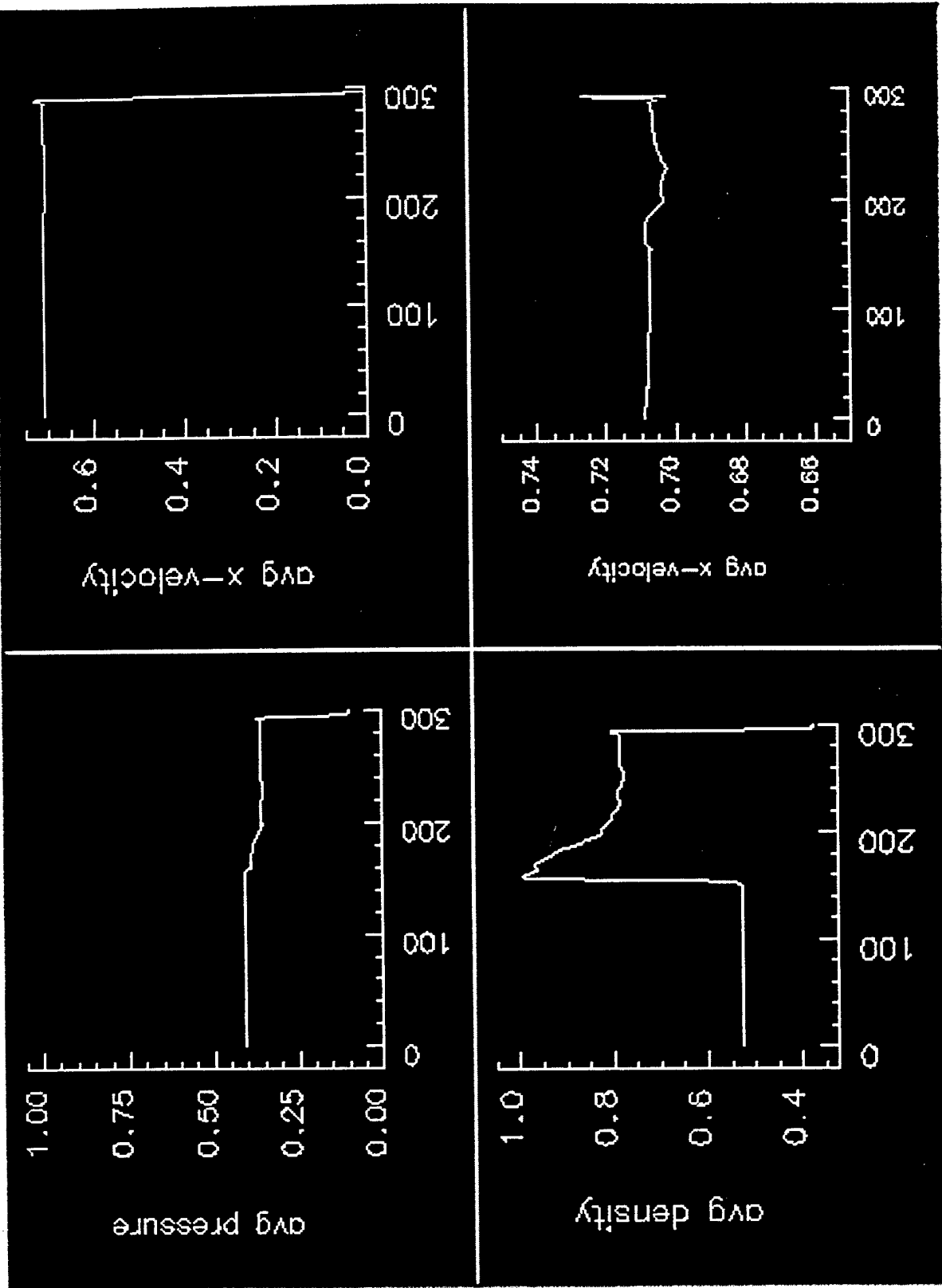
Profiles behind the contact discontinuity.



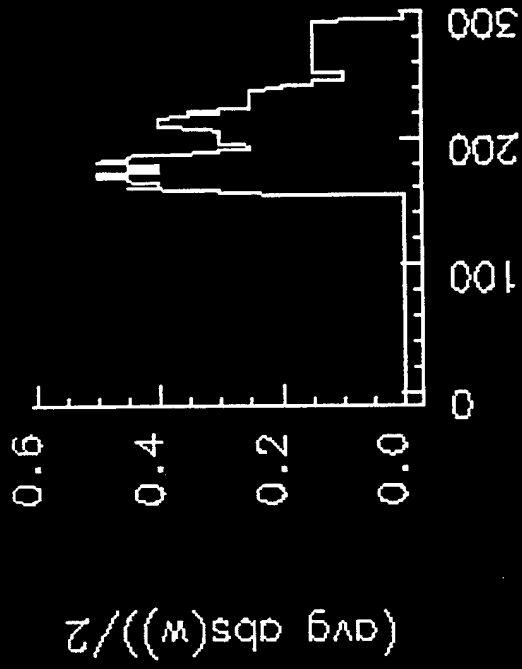
Shock-Jet System



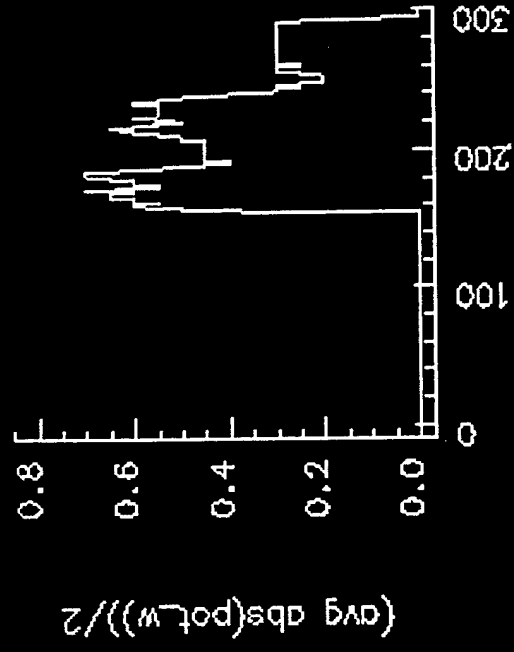
Averaged p, u_x, ρ



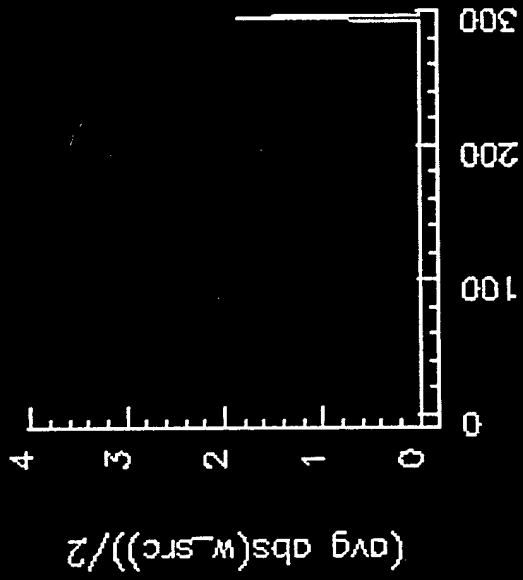
averaged vorticity



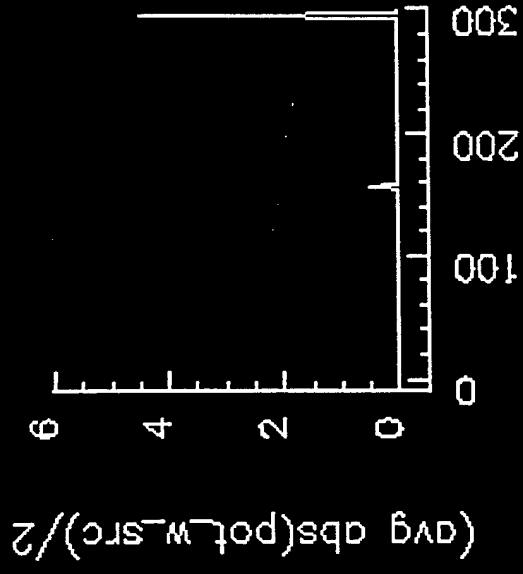
averaged potential vorticity



avg. rate of vorticity generation



avg. rate of pot. vorticity generation



RSI

Research
Support
Instruments

**Further Investigation of Large Volume PIA
(Persistent Ionizationin Air) Plasmas at
Atmospheric Pressure**

Mr. John F. Kline

Dr. John E. Brandenburg

Research Support Instruments

Lanham, Maryland

Presented at the Understanding and Control of

Ionized High-Speed Flows Workshop

Session IV: Plasma Generation and Maintenance

Princeton University

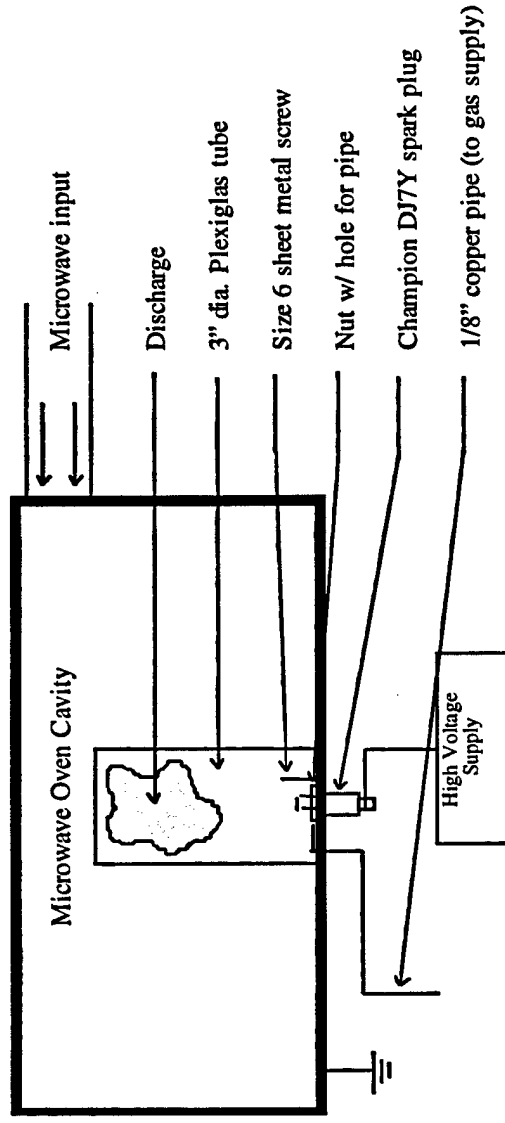
February 26, 1998

RSI

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Materials and Methods 2.45 GHz (1)

- Untuned cavity
- Field Enhancer
- Gas supply
- UV source
- Containment vessel

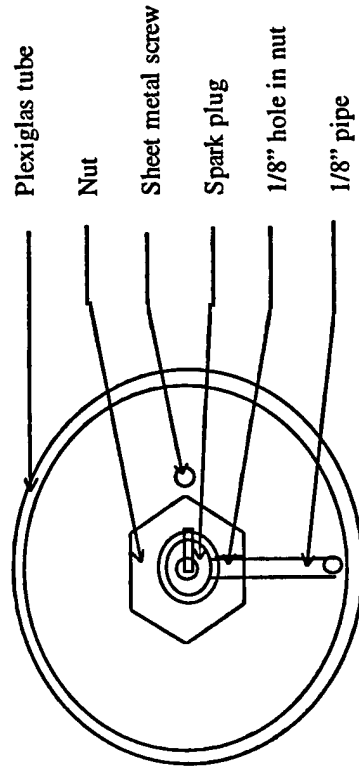


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Materials and Methods 2.45 GHz (2)

- Top view of apparatus
- Gases - stagnant air, nitrogen, argon, and helium
- Langmuir single probe
- Videocamera - frame counting
- Microwave detector
- Photocell to measure light decay time



Materials and Methods 2.45 GHz (3)

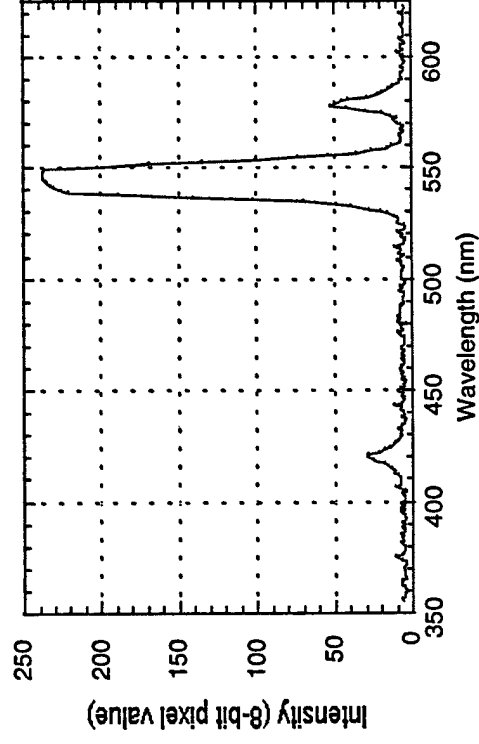
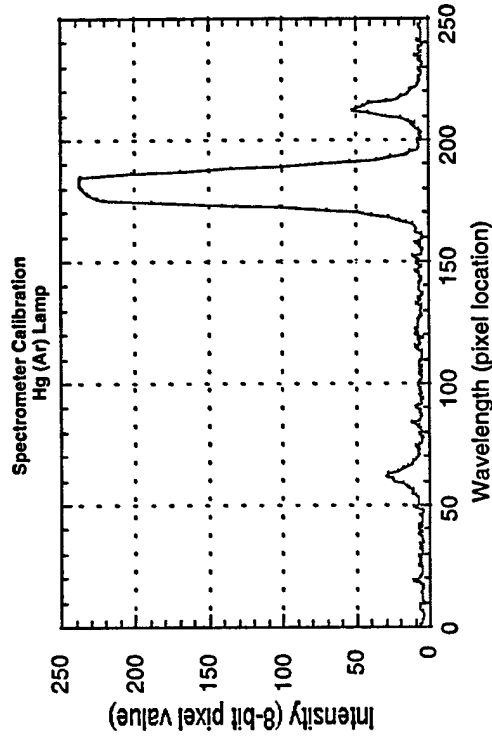
- Replacement of spark plug by laser induced breakdown
 - » 1.06 μm , 0.3 - 1 J, 10 Hz Nd-Yag laser
 - » Field enhancement still necessary for microwave breakdown
 - » Elimination of field enhancer by using TM_{012} resonant cavity
- Vortex ring generator to provide local E/P enhancement
 - » Loudspeaker with plastic cone using voltage pulses
 - » Shapes plasma into flat disc that follows vortex ring
- Emissions spectra measurements
 - » 8-bit CCD viewing exit aperture of spectrometer
 - » Pixel values over a line give a time-resolved measurement over a broad range

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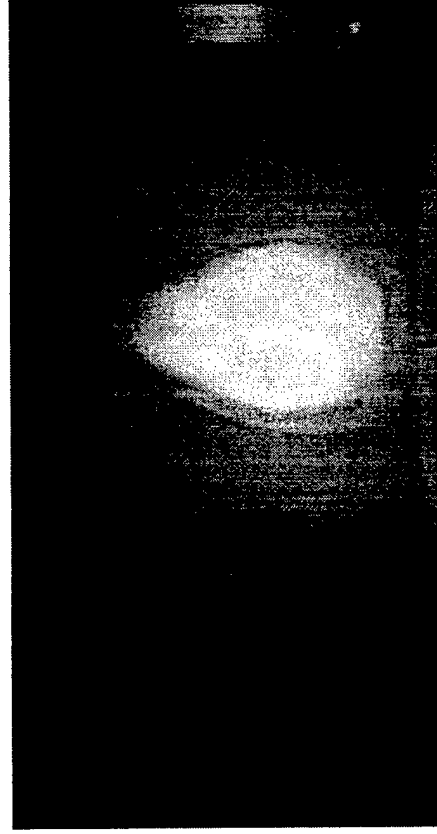
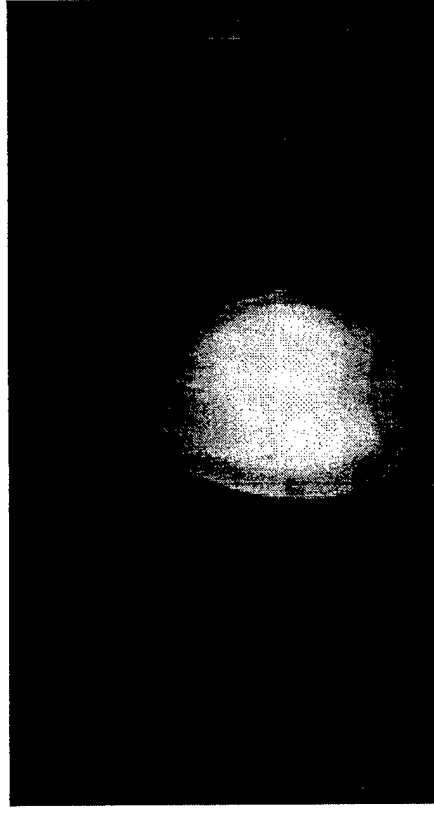
Materials and Methods 2.45 GHz (4)

- Time-resolved emissions spectra
- Broad range of wavelengths
- Pixel depth vs. position yields intensity vs. wavelength
- Calibration using Hg (Ar) source



Results (1)

- Temperature - 0.67 eV
- Density - 10^{10} cm^{-3}
- Low neutral gas temperature
- Turbulent, with toroidal core
- Optimal flow rate - 1.2 LPM
- Volume - 280 cm^3 average
- Microwave shielding - 1 order of magnitude increase with plasma (indicates 10^{11} cm^{-3})

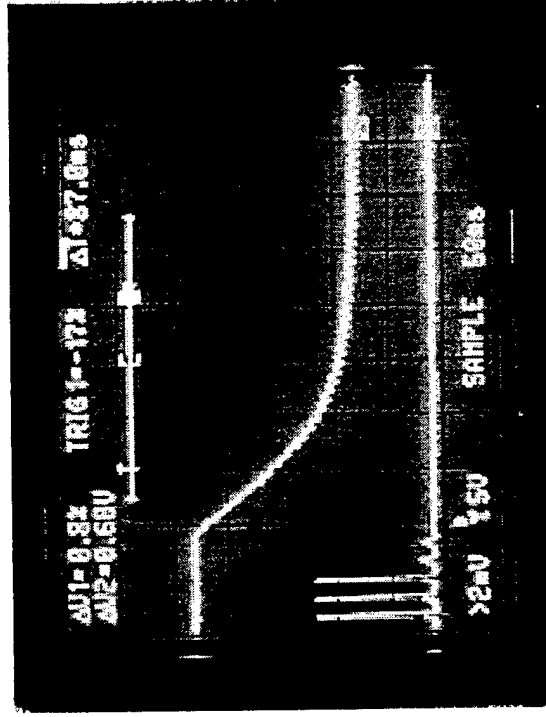


RSI

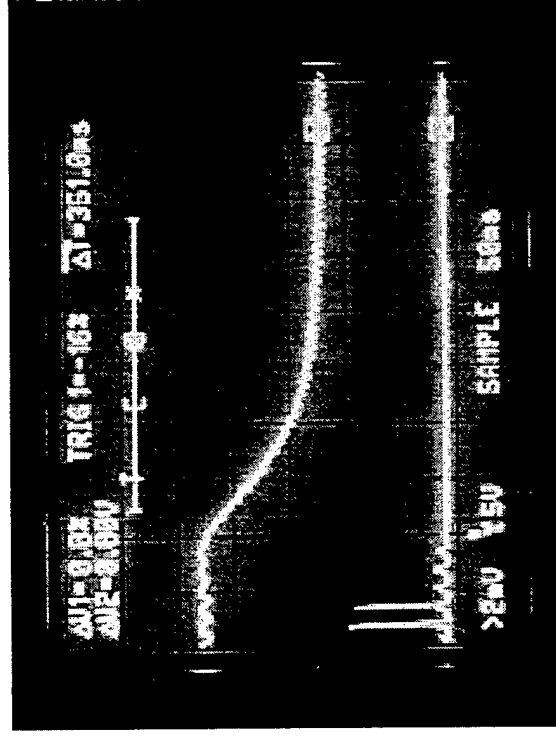
Research
Support
Instruments

Results (2)

- Unpowered lifetime - 200 ms average (3 e-folds at 60ms decay time)
- Upper channel shows photocell output
- Lower channel shows microwave detector output



Argon



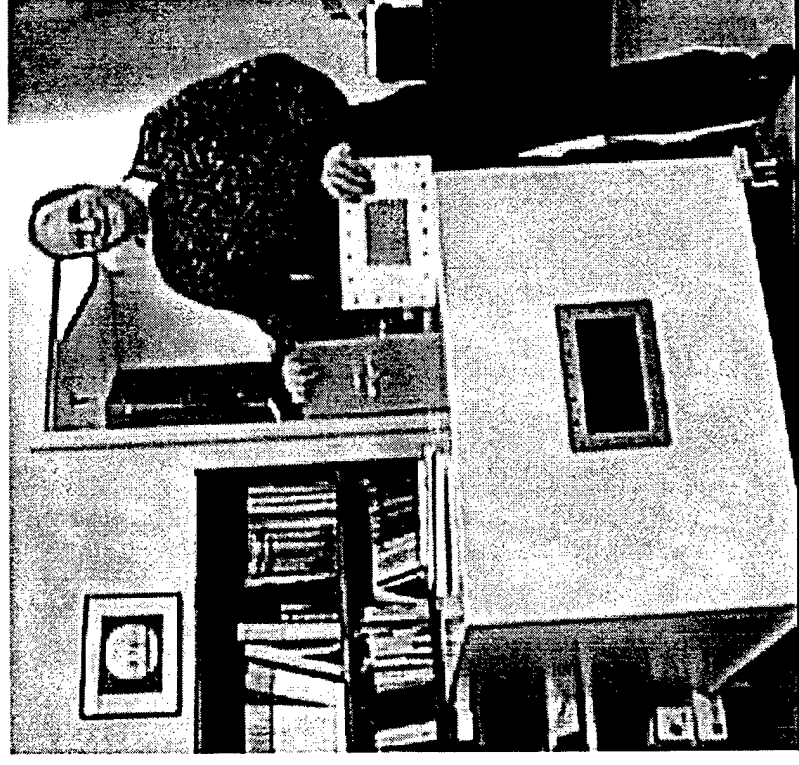
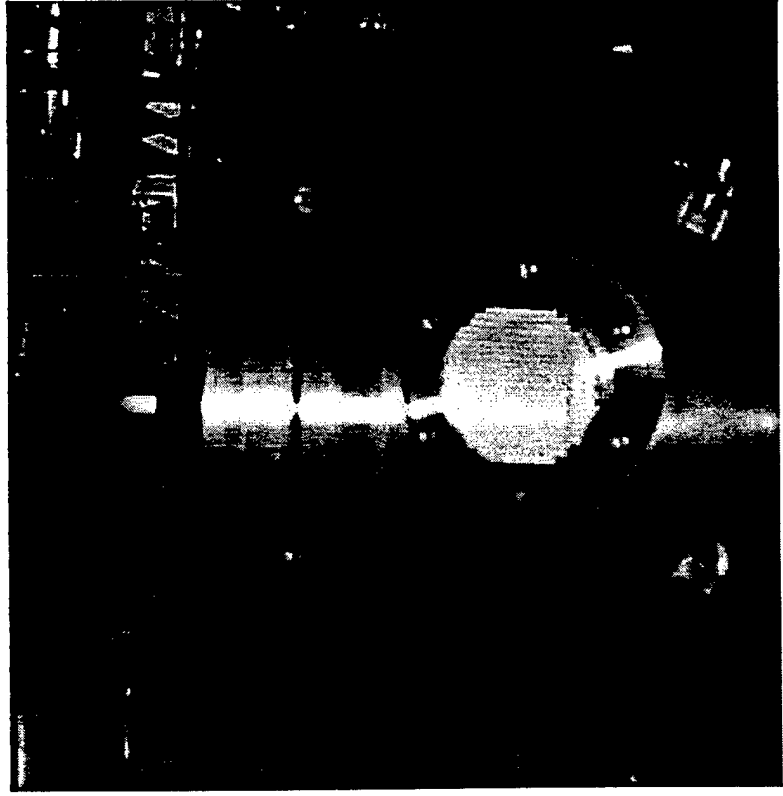
Air

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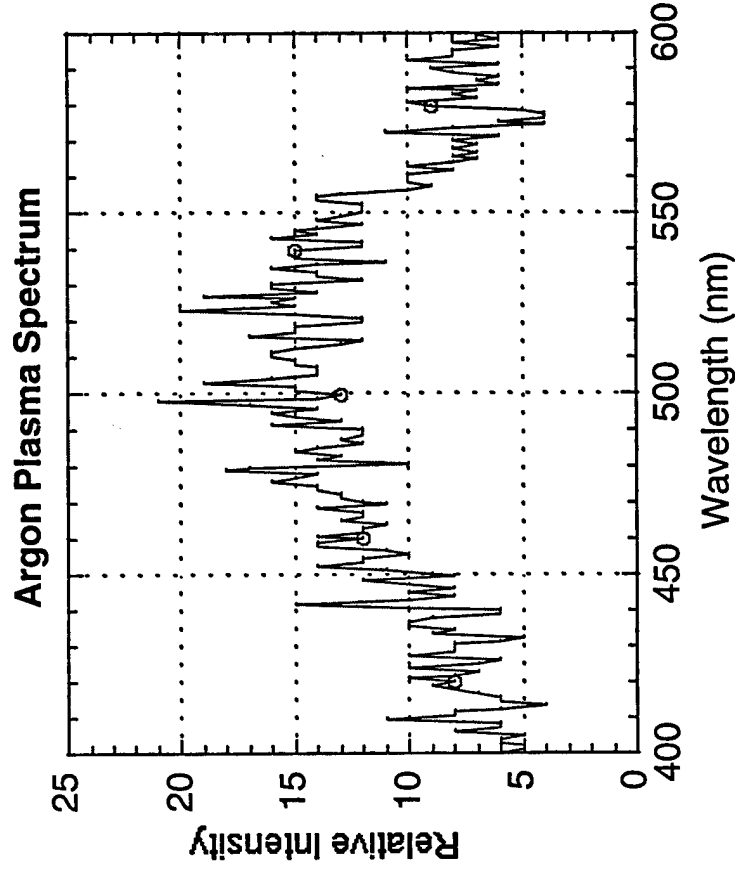
Results (3)

- Scaling of TM_{011} resonant cavity to 0.915 GHz
- 45 kW operation using vortex-stabilized compressed air



Results (4)

- Initial data on argon mixture
- Shows broad continuum (previously seen at Stanford)
- Can acquire time history data



Discussion

- Shared Electron Orbital (SEO) Hypothesis
 - » Decoupling of electrons from collisions with neutrals
 - » Long collisional energy transfer times
 - » Long recombination times
 - » Electrons shared between orbitals
 - » Resemble conduction bands in liquid metals
 - » Vorticity suggests trapped magnetic fluxes and dynamo action (as in liquid metals)

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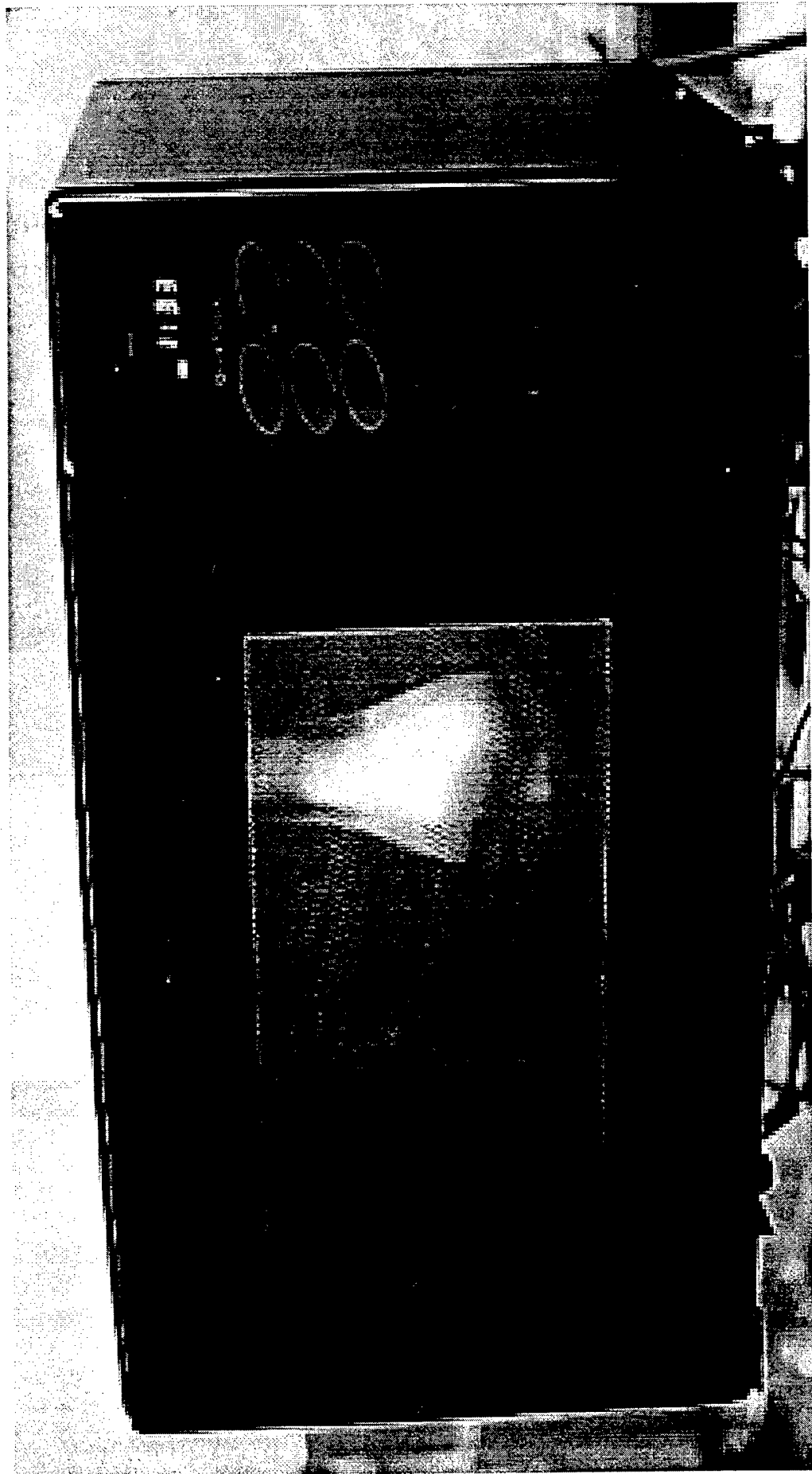
Future Work

- Advanced diagnostics
 - » Continuing work on emissions spectra
 - » Triple probe with digital oscilloscope and function generator
- Investigate vorticity
 - » Pulsed power vortex ring generator
 - » Optically measure rotation

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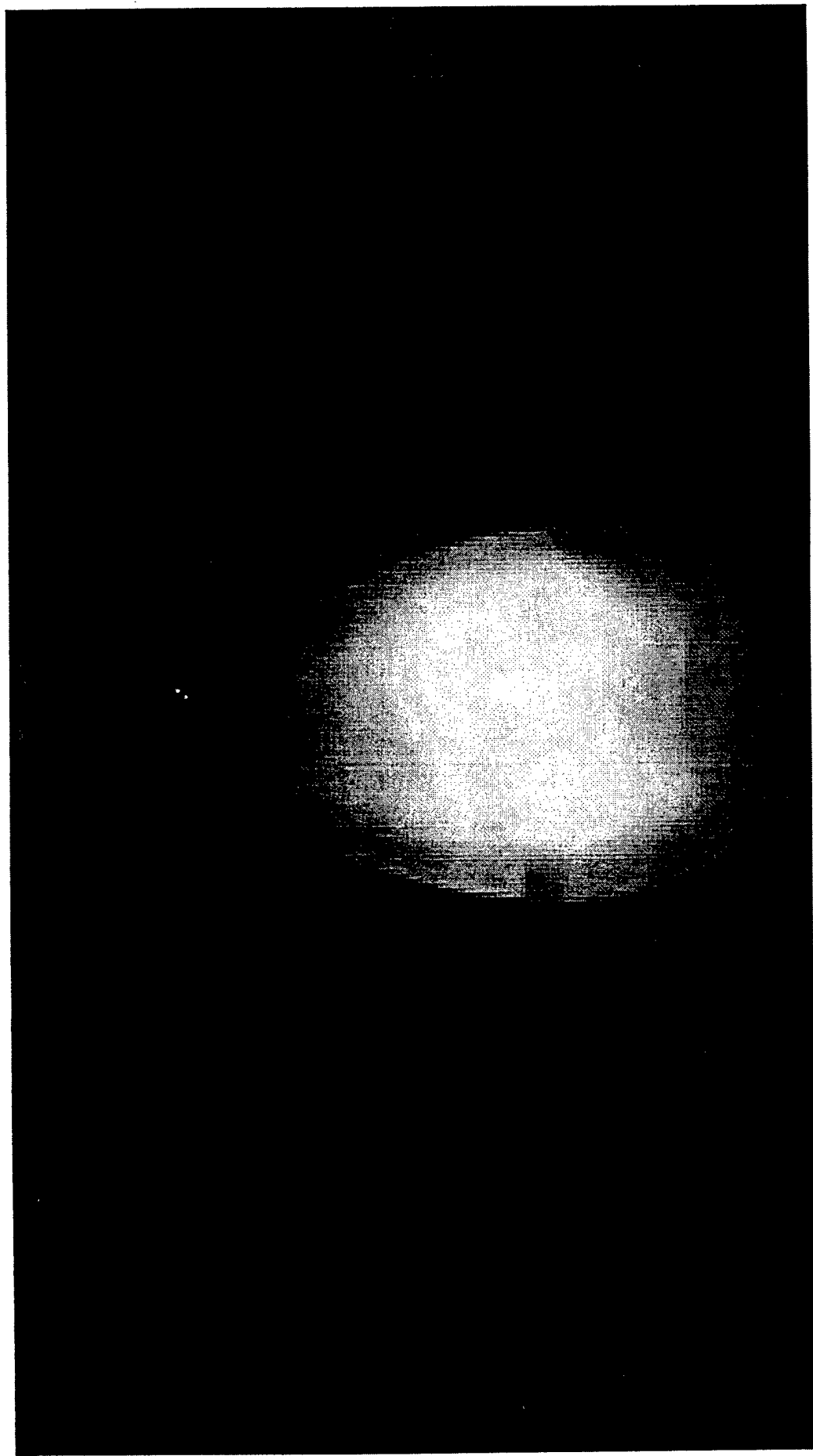
Nitrogen Plasma - Low Flow



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Instruments

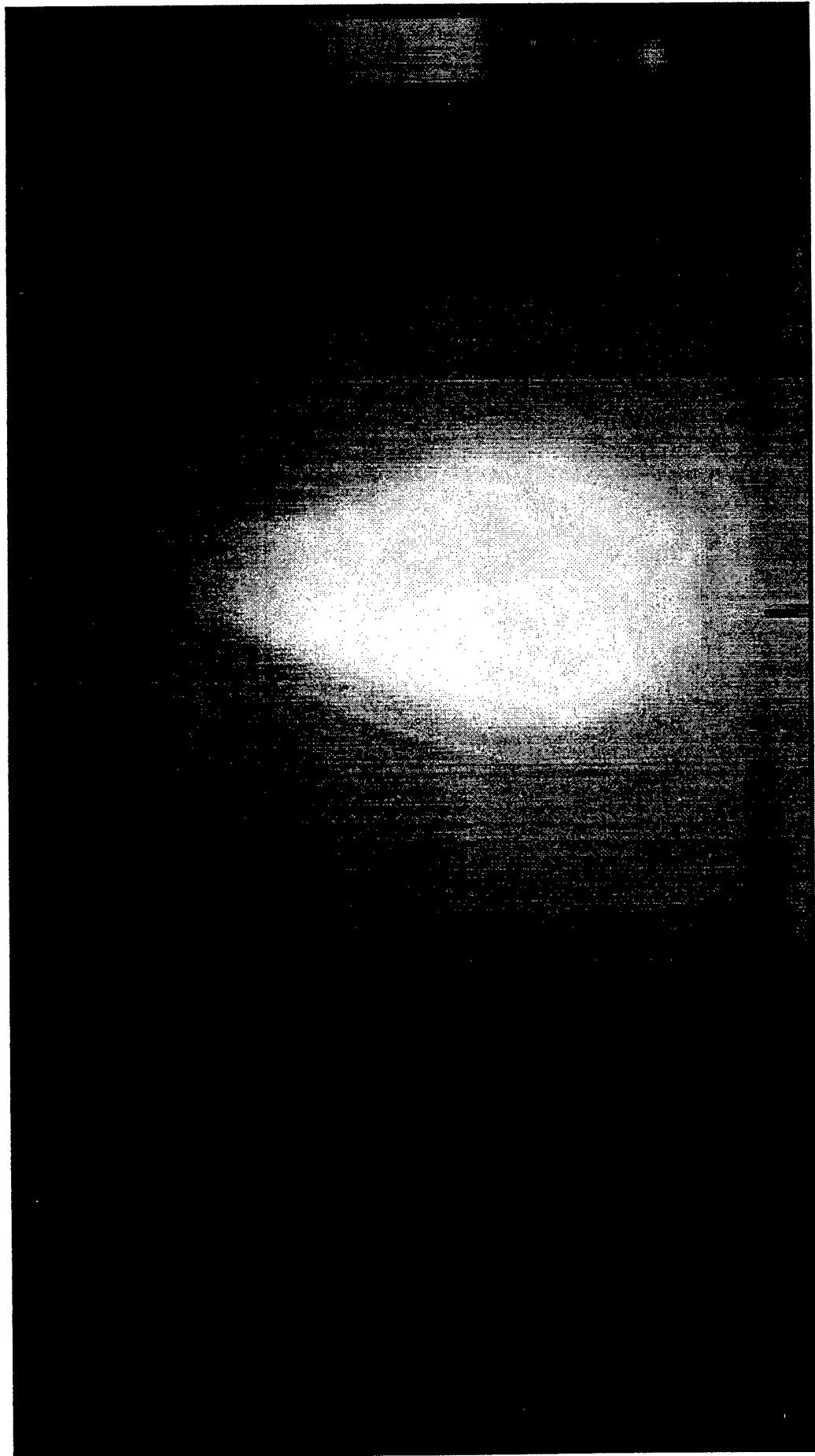
Nitrogen Plasma - Stable



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Argon Plasma - Stable



Plasma Torches and Their Demonstration

Spencer P. Kuo and Edward Koretzky

Department of Electrical Engineering

Polytechnic University

***Work supported by the AFOSR**

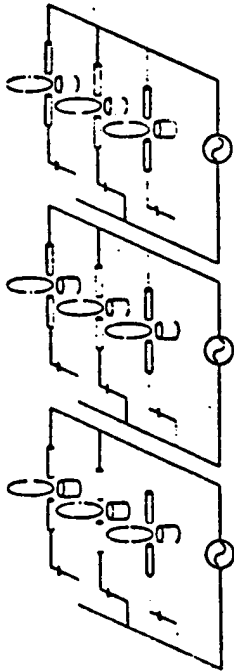


Figure 1.1: A schematic of the current arrangement for an array (3×3) of plasma torches. Tungsten electrodes are used. Each electrode pair is facilitated with an air jet nozzle.

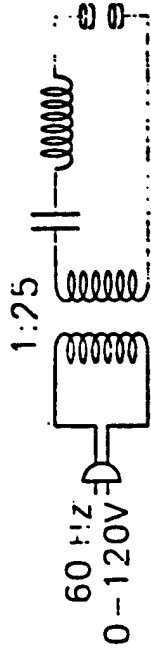
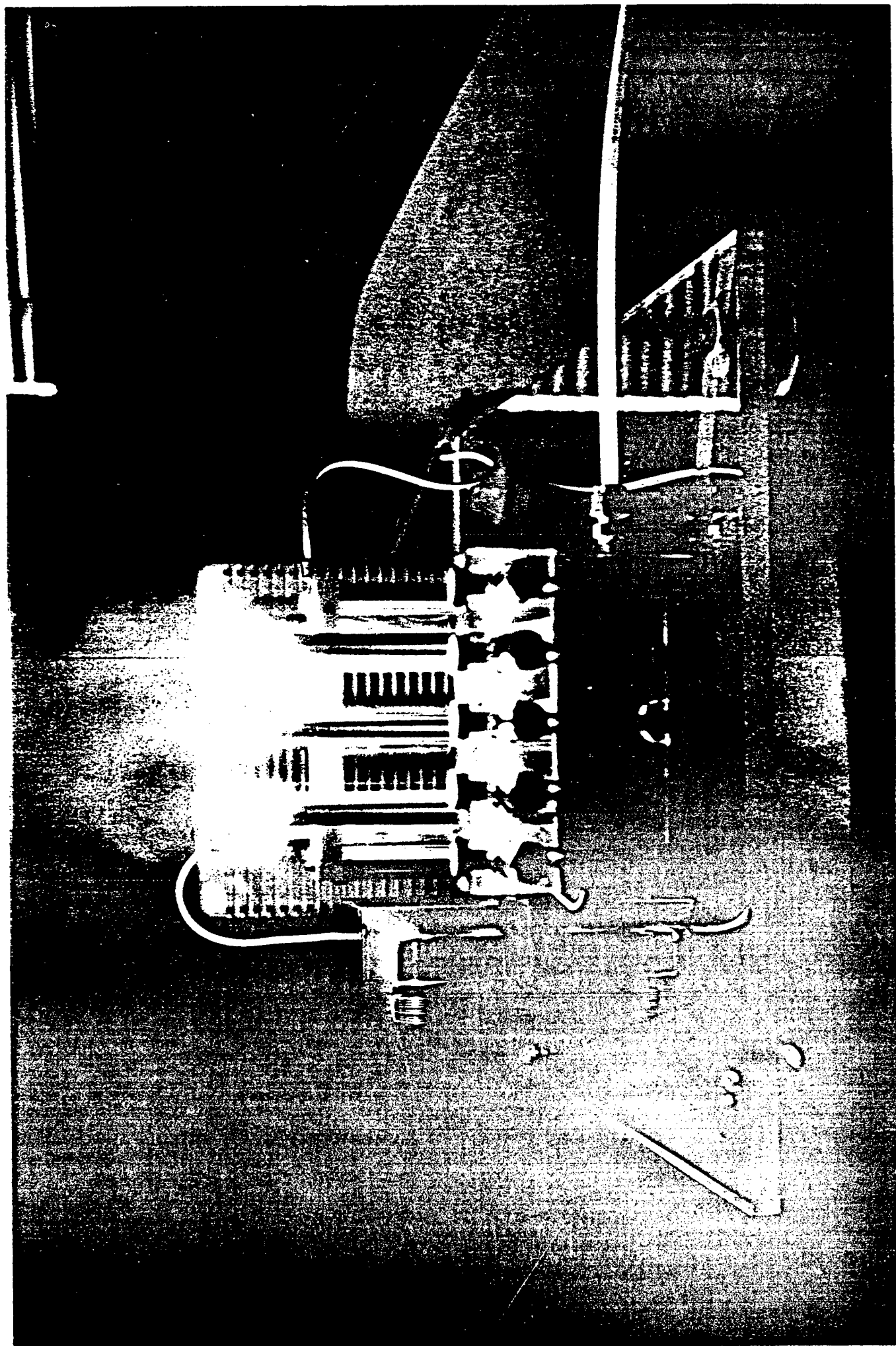
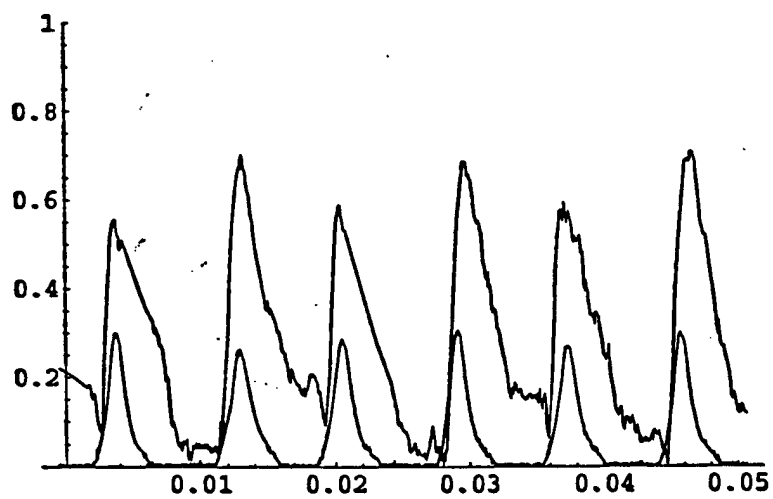
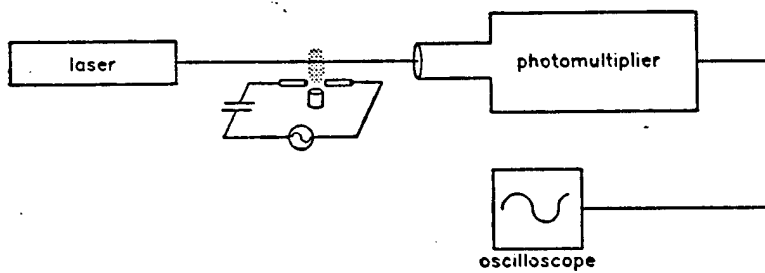
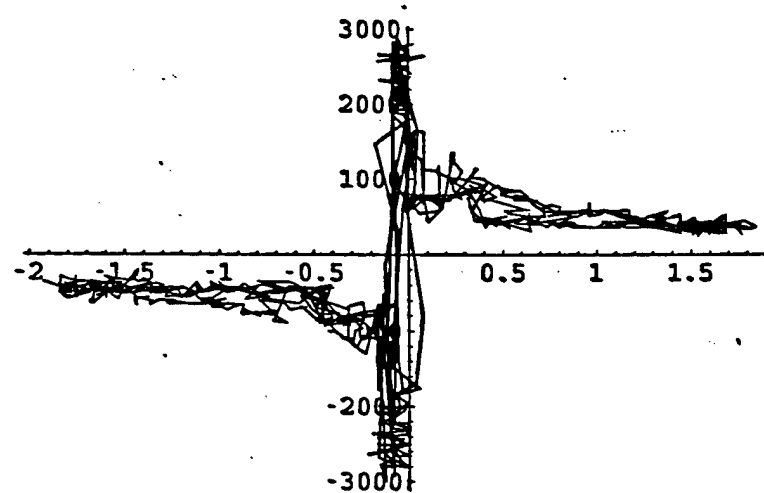
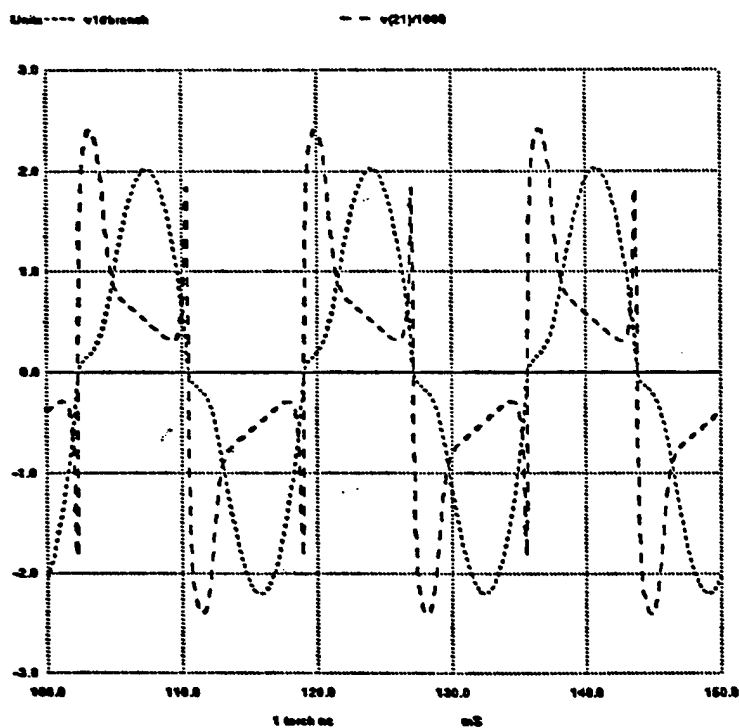
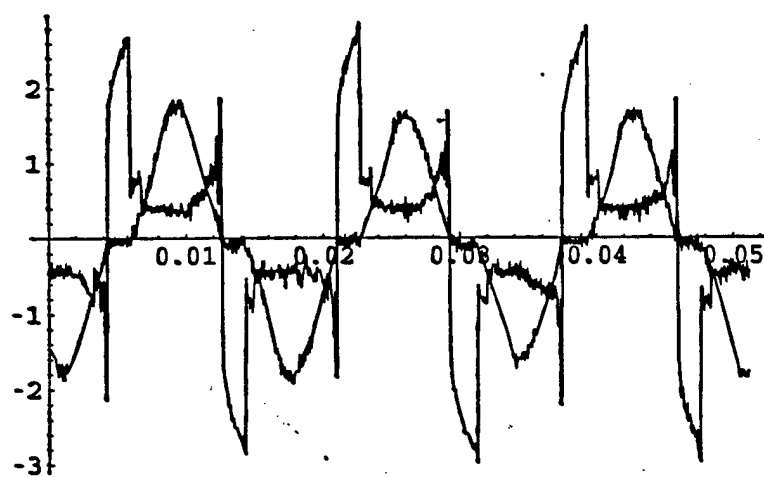


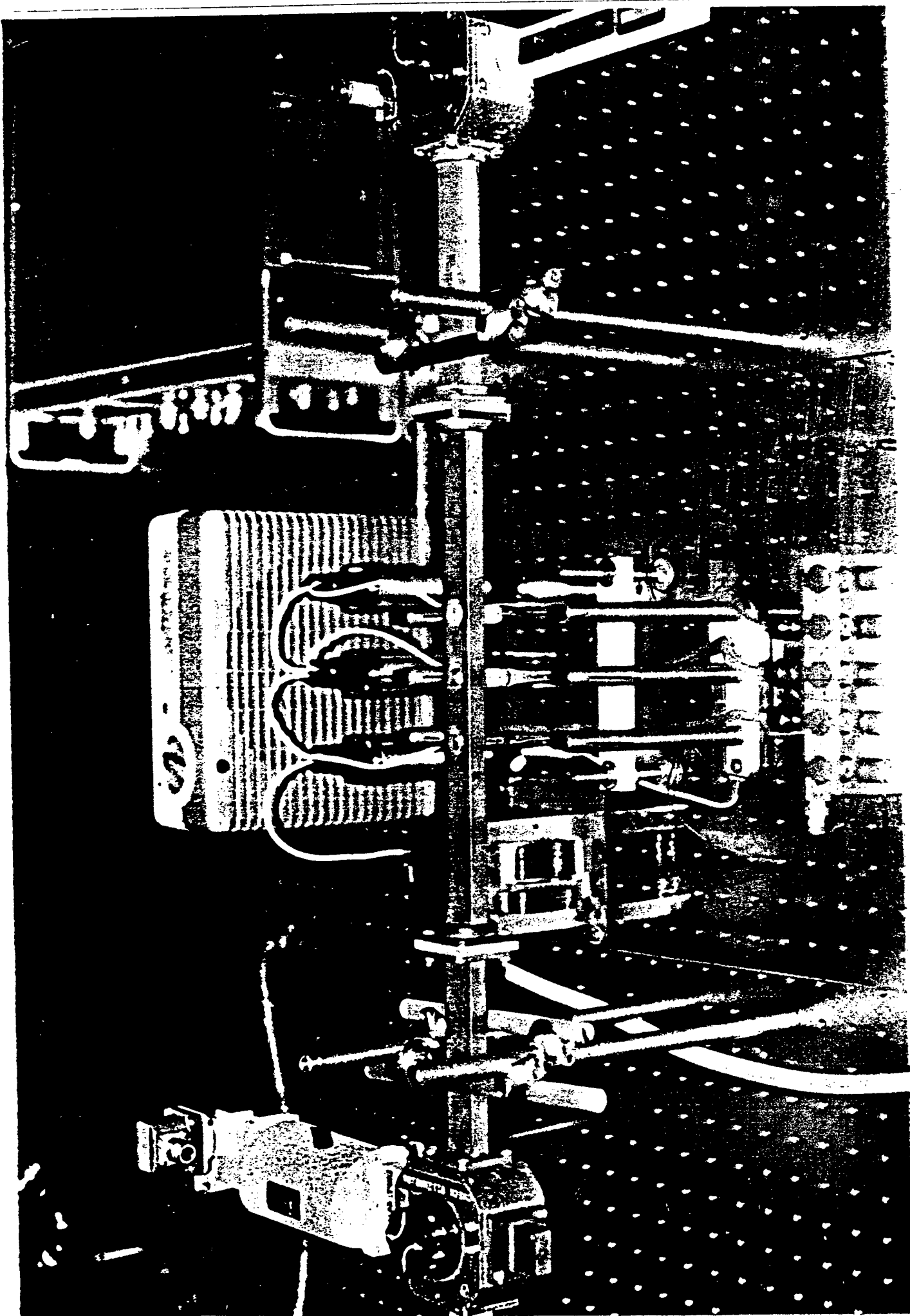
Figure 1.2: Circuit diagram of the plasma torch.

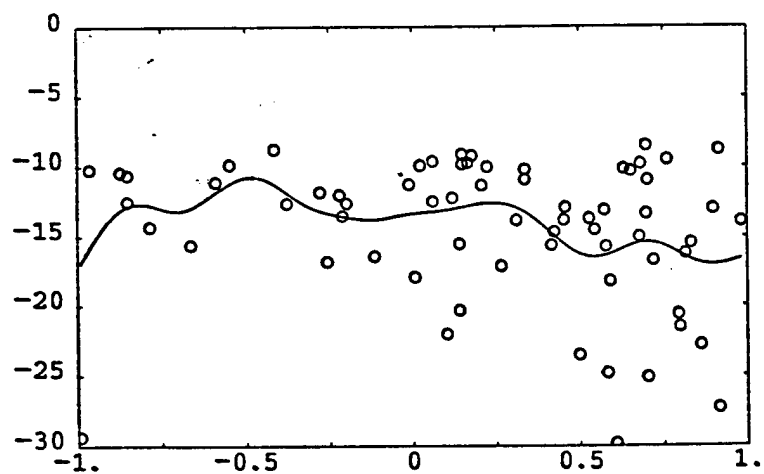
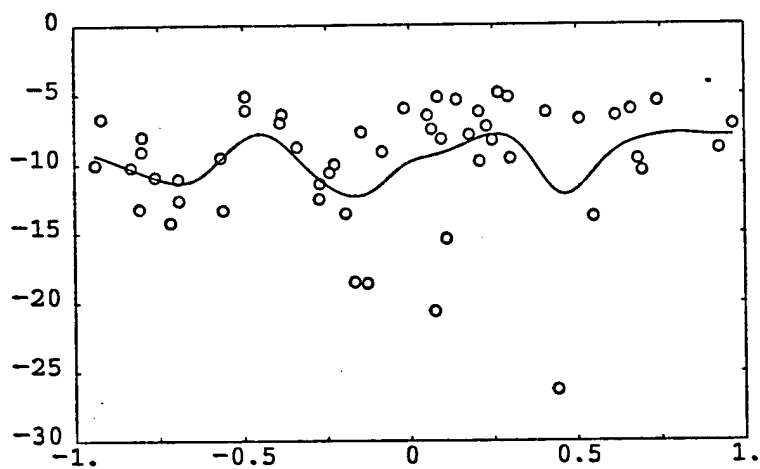
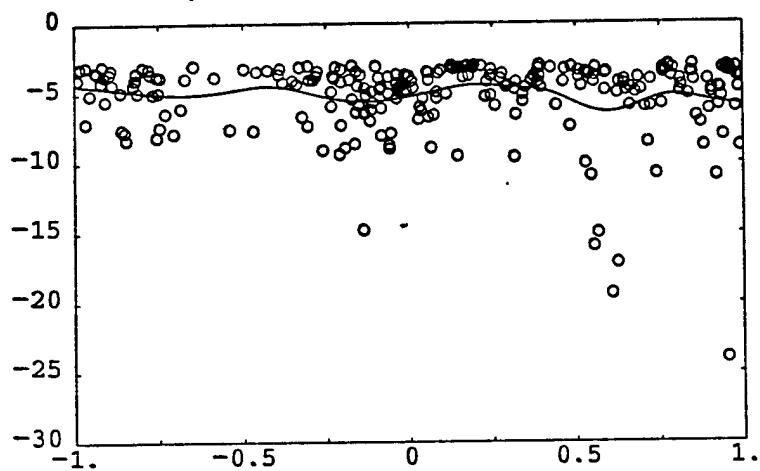


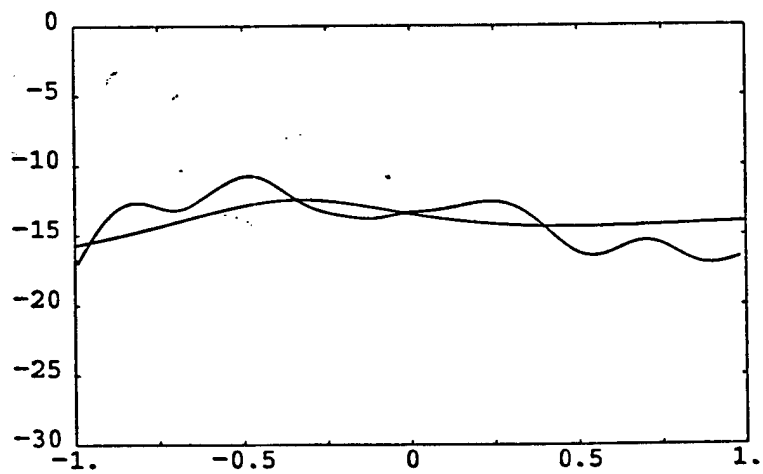
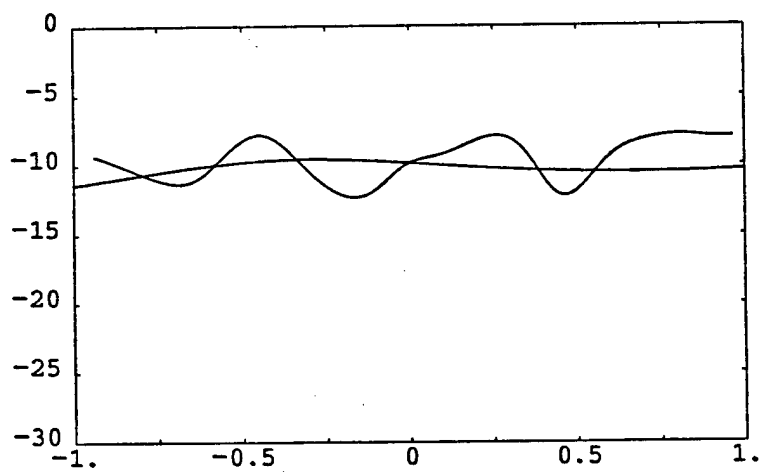
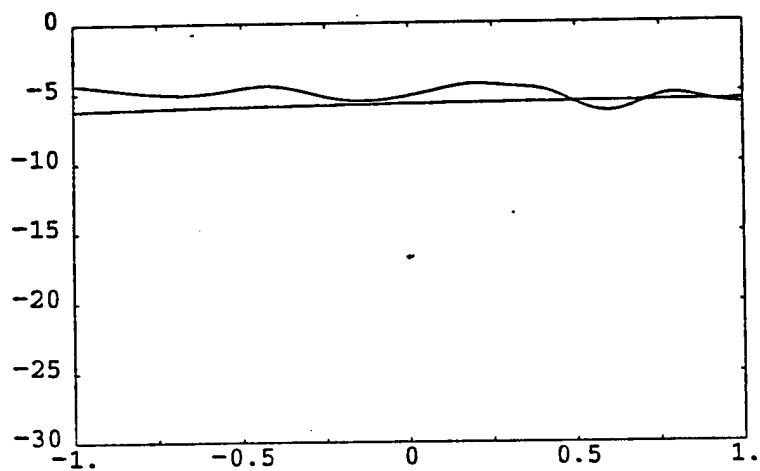










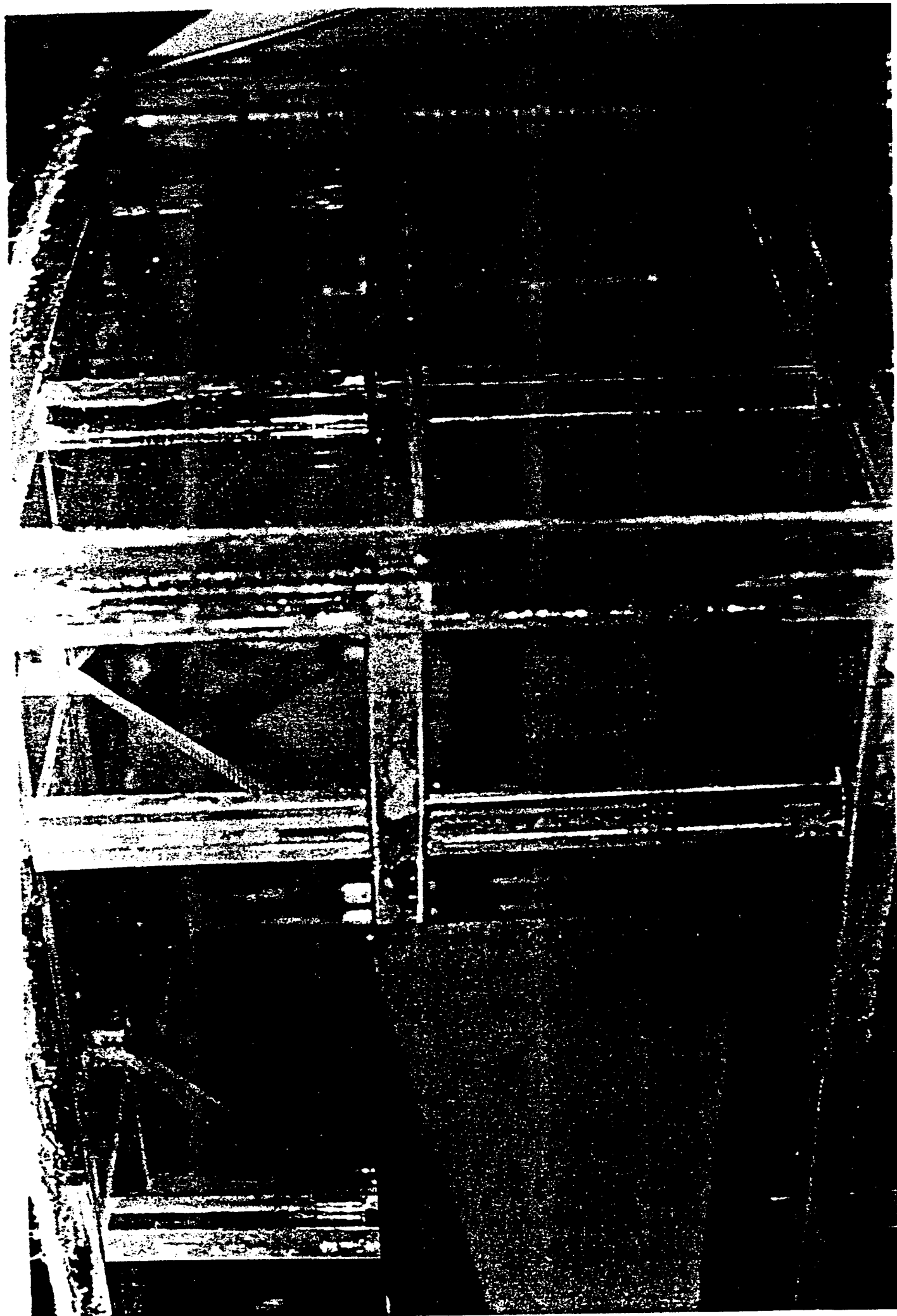


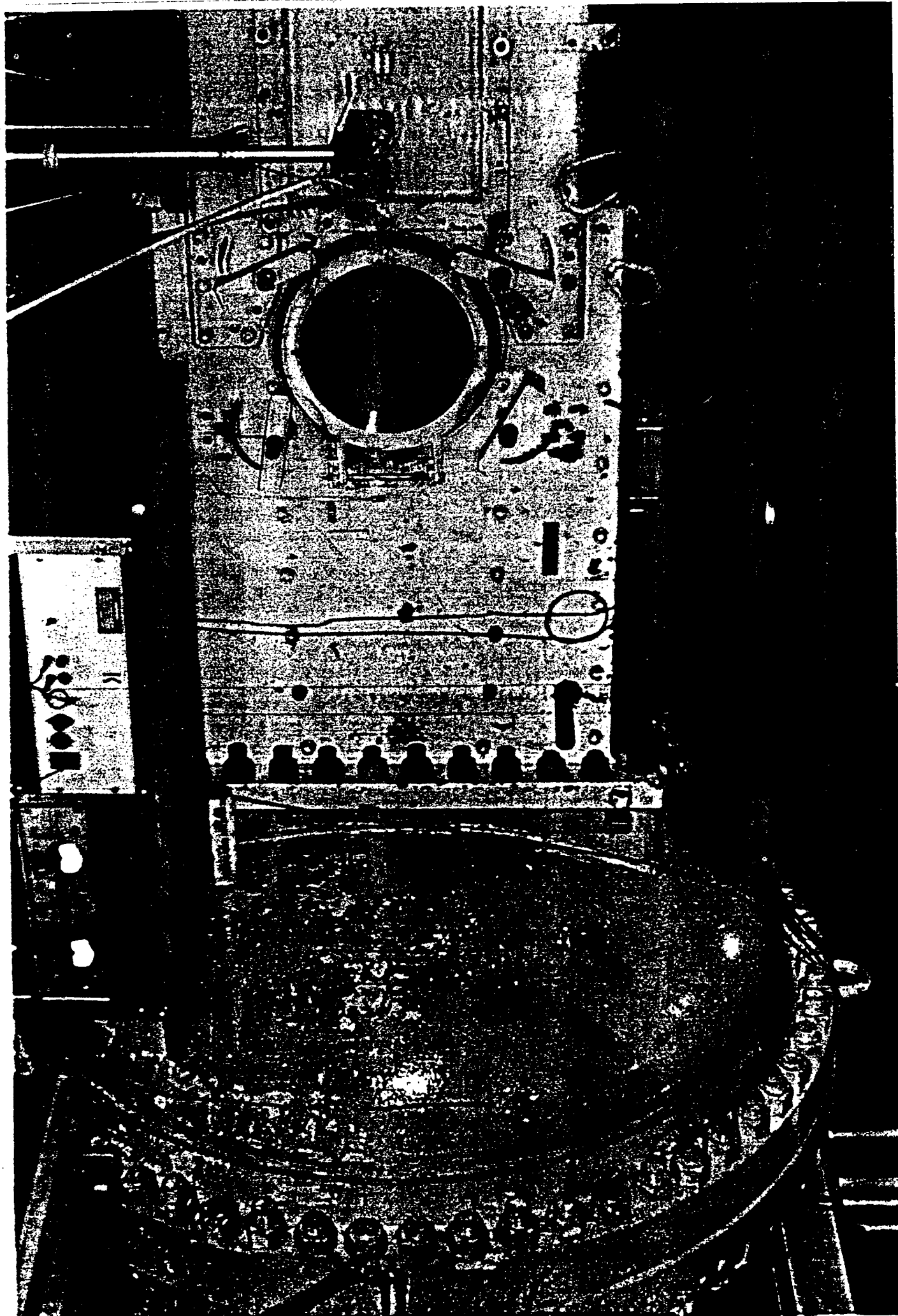
Plasma Torch

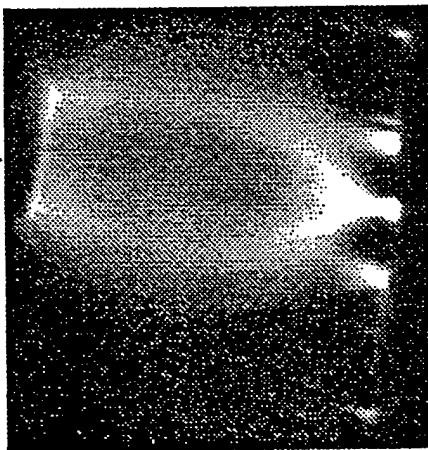
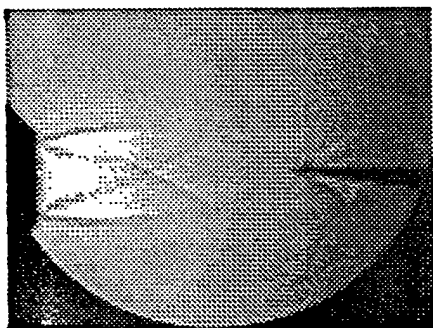
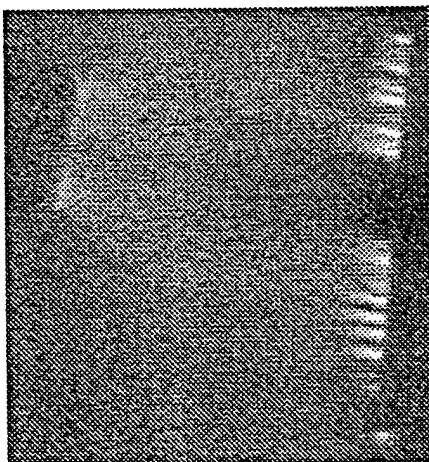
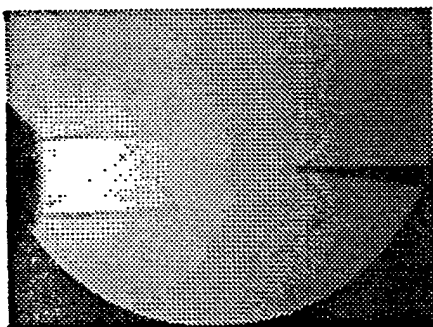
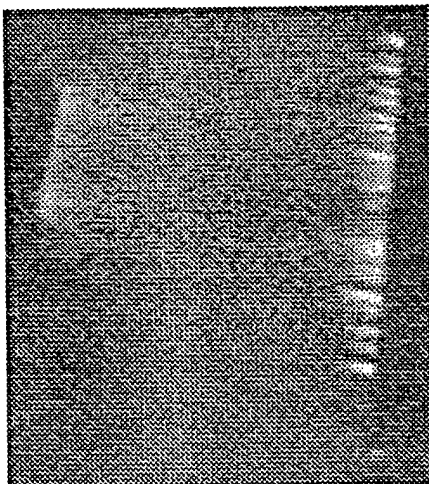
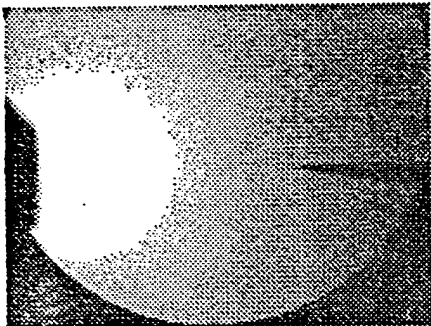
Pressure:	1 ATM
Density:	1.5×10^{13} (deduced from measurements based on two independent methods)
Temperature:	$1200^\circ K$
Dimensions:	cylindrical shape having 1 cm radius and 7 cm length
Volume:	$20 \text{ cm}^3/\text{torch}$
Power Consumption:	600 W/torch
Peak Voltage and Current:	2.8 kV and 2 A

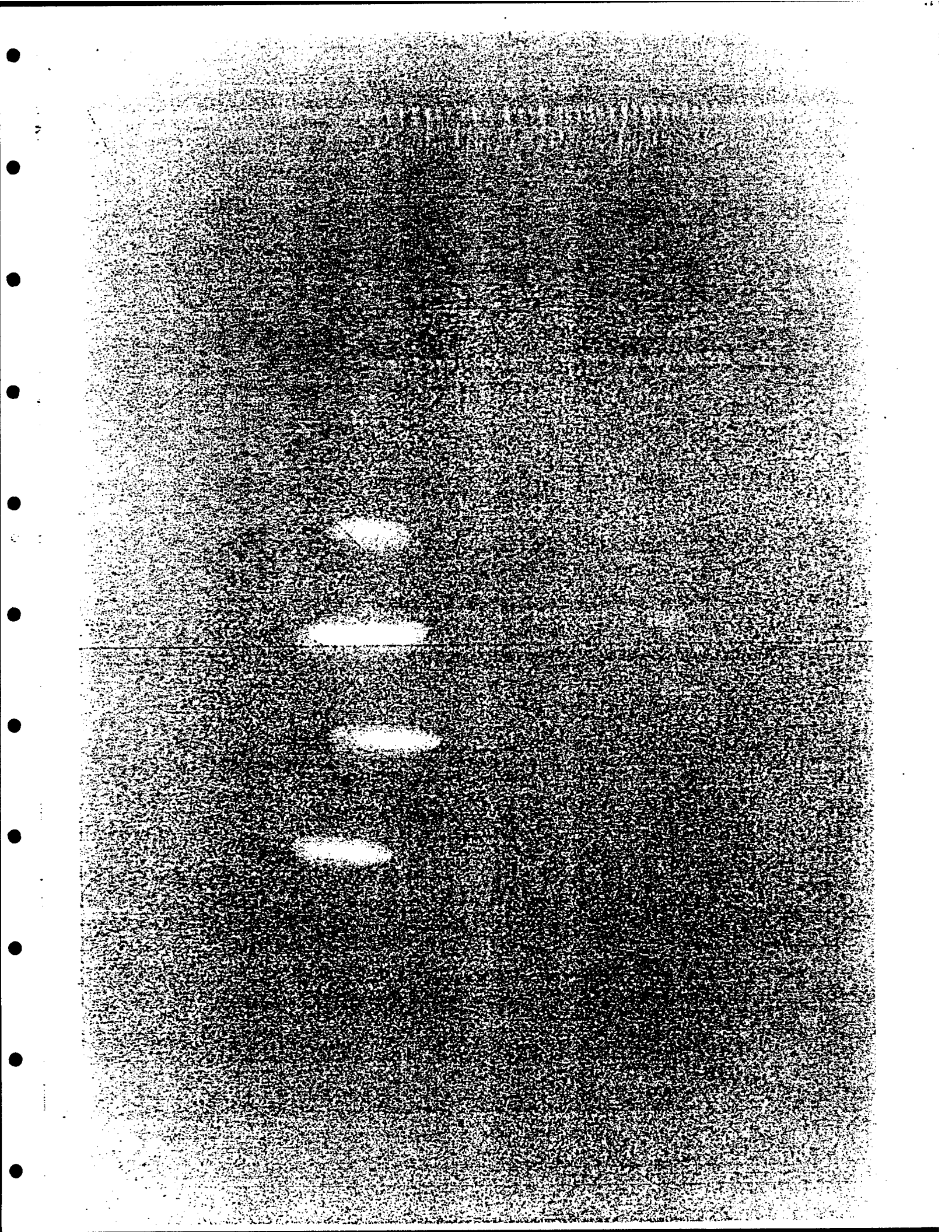
Microwave Plasma Layers

Pressure:	20 torr
Density:	10^{11} cm^{-3}
Microwave Power:	1 MW peak, 1 μs pulse, 40 rps









**Plasma Ramparts Using
Metastable Molecules**

MURI Program

**The Ohio State University
Princeton University**

**"Optically Pumped Nonequilibrium
Plasmas"**

I. Adamovich, V. Subramaniam, W. Rich

Presented at

AFOSR Workshop

**"Understanding and Control of
Ionized High-Speed Flows"**

**Princeton University
Feb. 26-27, 1998**

**Work funded by the Director of Defense Research &
Engineering (DDR&E) within the Air Plasma Ramparts
MURI Program managed by AFOSR**

Program Objectives:

- **Create large volume ($O[m^3]$) free air plasma**
- **One atmosphere**
- **Free electron densities 10^{13} cm^3 or greater**
- **Gas temperature less than 2,000 K**
- **Energy efficient method**

Approaches:

A. Thermal Plasmas (High Temperature Arcs, Reentry Plasmas)

Problems:

I) High Temperature

B. NonThermal Plasmas (Glow Discharges, Optically Pumped Plasmas)

Problems:

I) Requires thermodynamic work (electrical work, laser work)

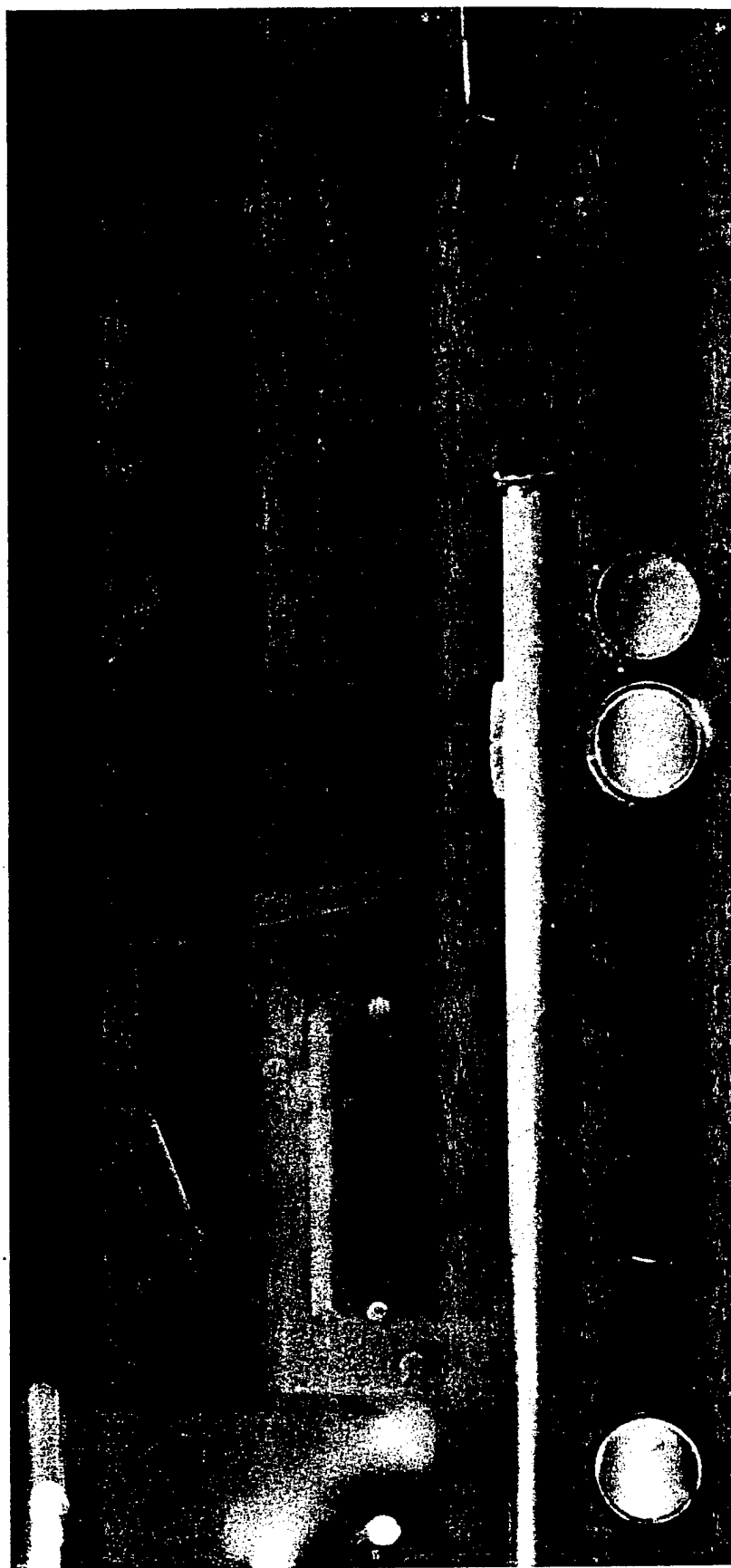
II) Stability

OSU/Princeton Approach: Laser Pumped Metastable State Plasmas.

92 W cw broad-band lasing conditions

Date: 10-26-1992		
Gas	Partial Pressure (Torr)	mass flow rate (10^3 g/min)
He internal purge	4.15	18.9
He	9.00	75.5
N ₂	2.75	138
CO	1.60	6.61
Air	.01	.89
Total	17.5	239
He:CO:N ₂ molar ratio 751:92:157		
Discharge Conditions		
Current mADC	45	
Voltage kVDC	18	
Laser Power Broad Band W	92	
Physical Efficiency	30.3%	

The Ohio State University



Nonequilibrium Thermodynamics Laboratories

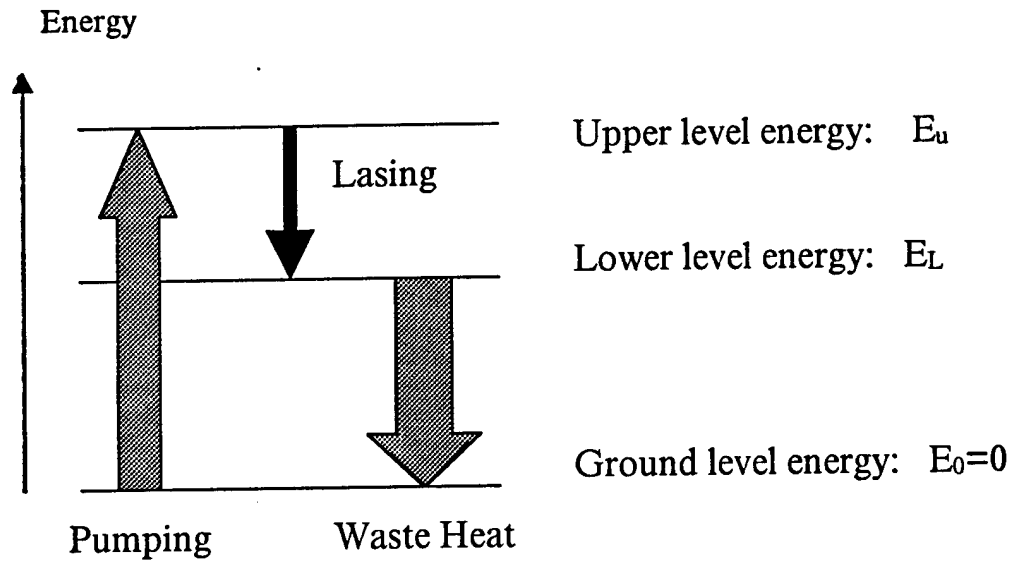
Advantages:

- **Stable, large volume**
- **High pressure**
- **Low gas temperatures**

Problems:

- **Electron density**
- **Efficiency**
- **Non-air species**

Three Level Laser



Quantum Efficiency

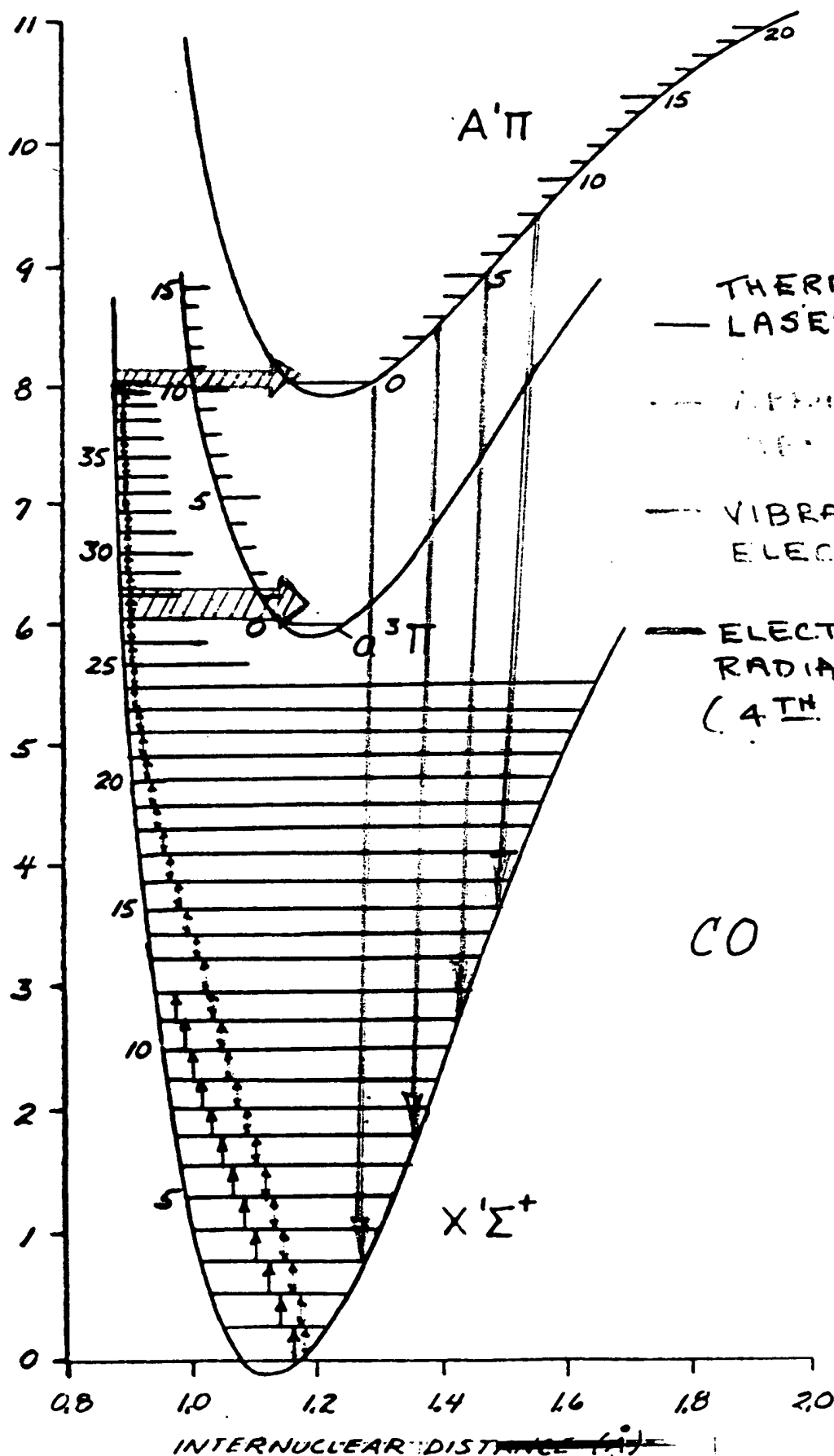
$$\eta_{\text{quantum}} = \frac{E_U - E_L}{E_L}$$

~ 40% for CO_2/N_2

~ 95% for CO/N_2

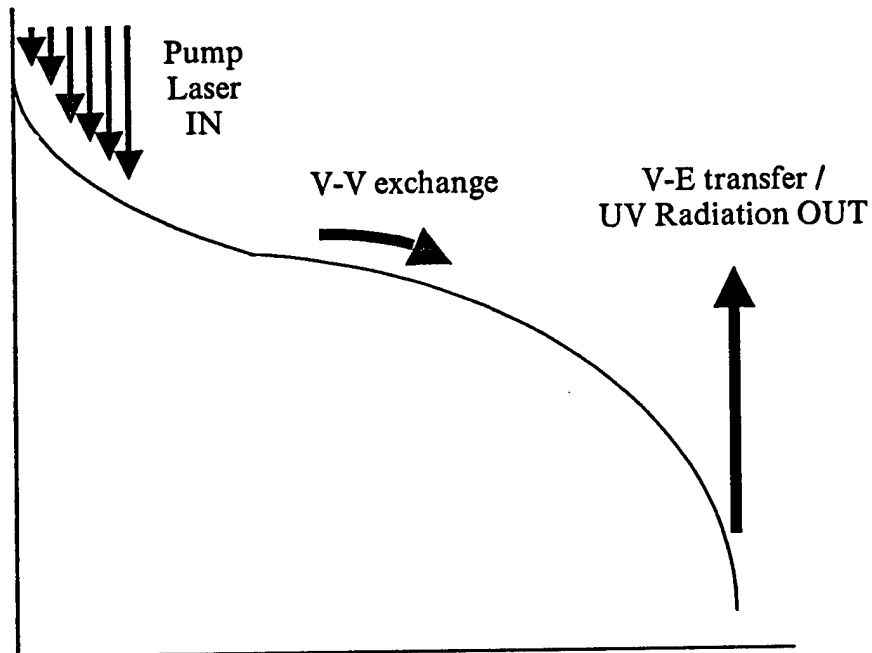
Scoville, 1954 showed equivalence
with reversible engine efficiency

POTENTIAL ENERGY (ELECTRON VOLTS)

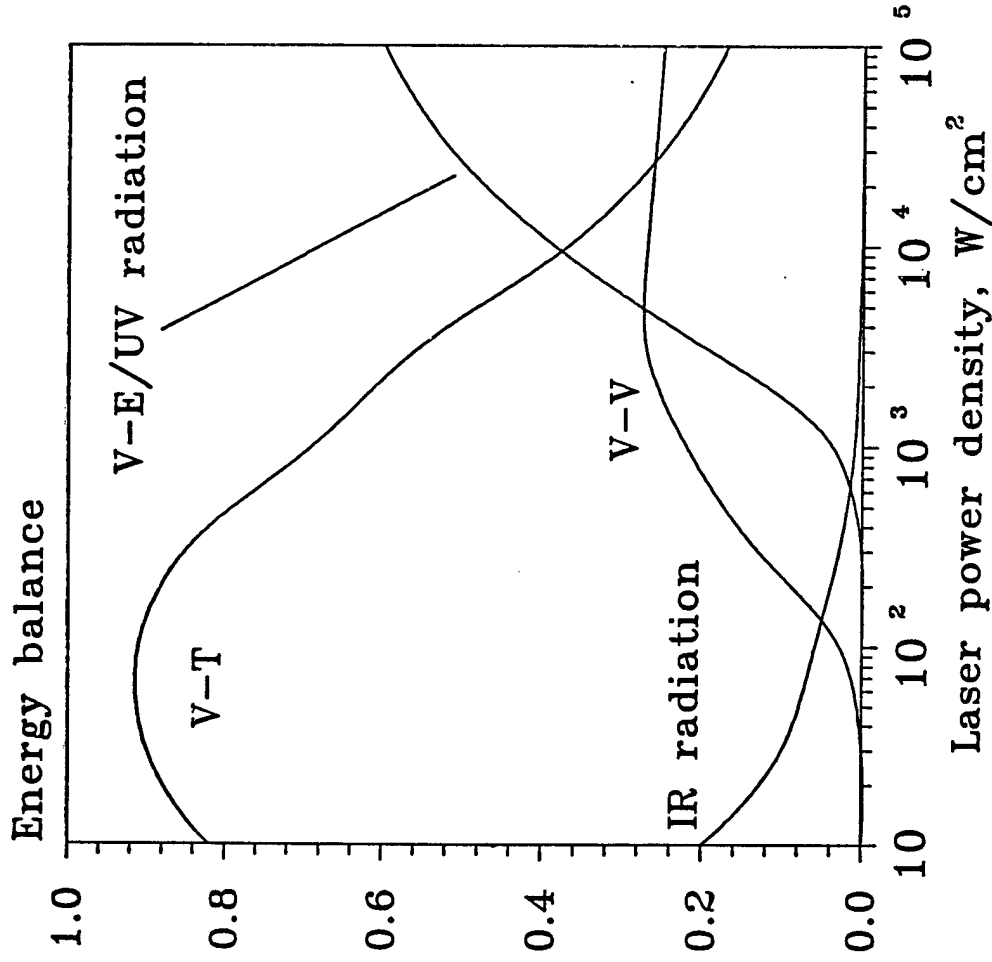


IR/UV Radiation Conversion in Optically Pumped CO-Ar Plasma

Relative population

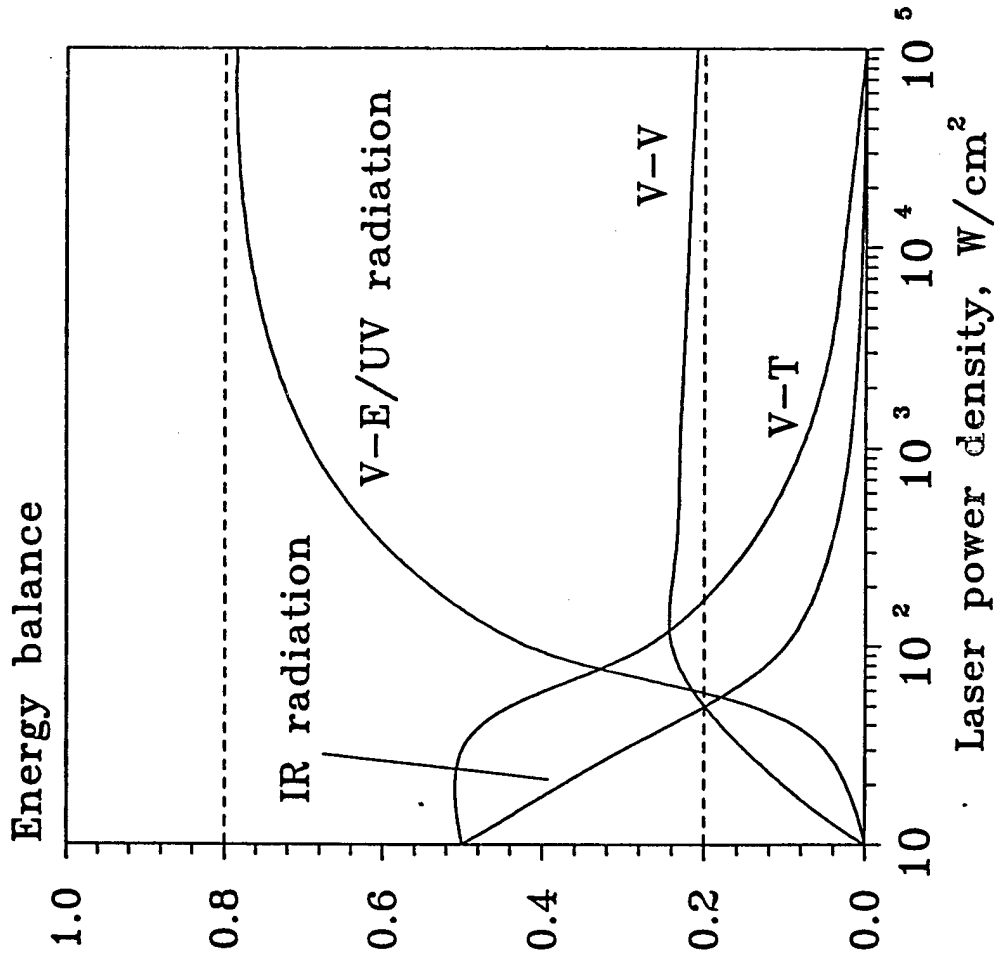


Vibrational Quantum Number

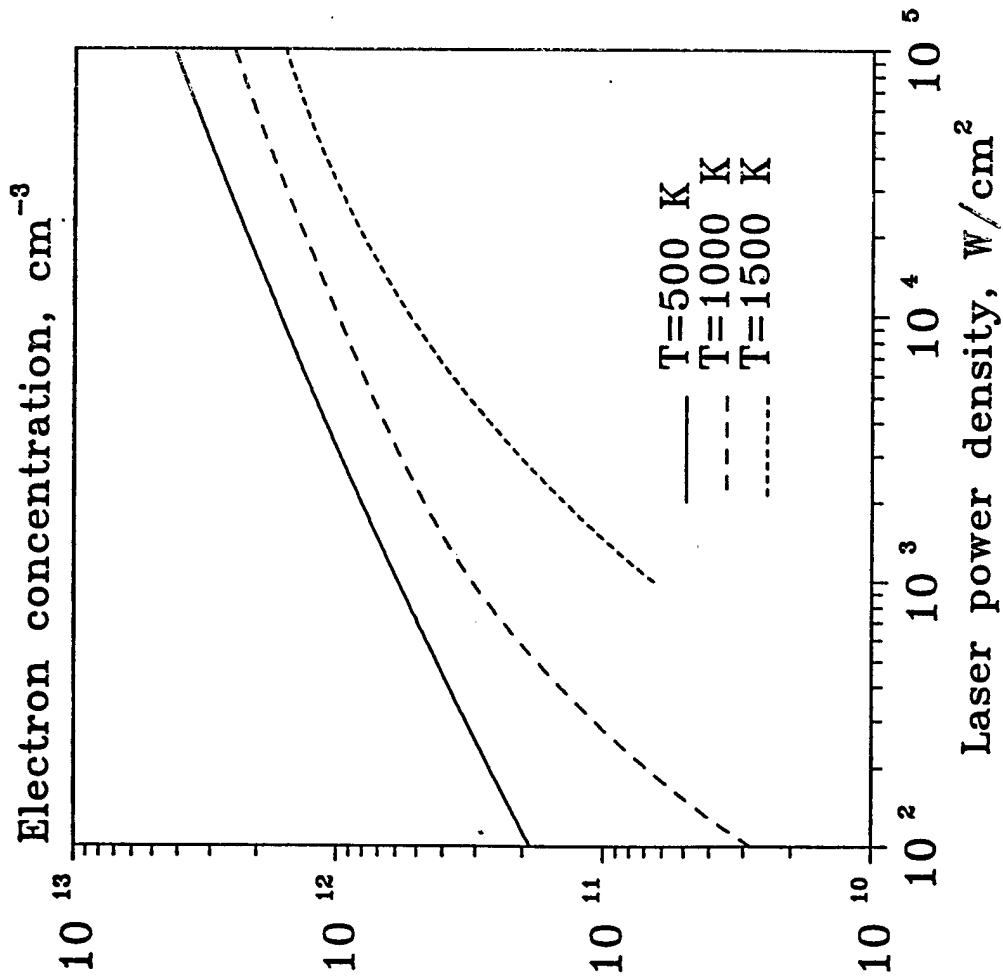


P=1 atm, T=1500 K

CO:Ar=5:95



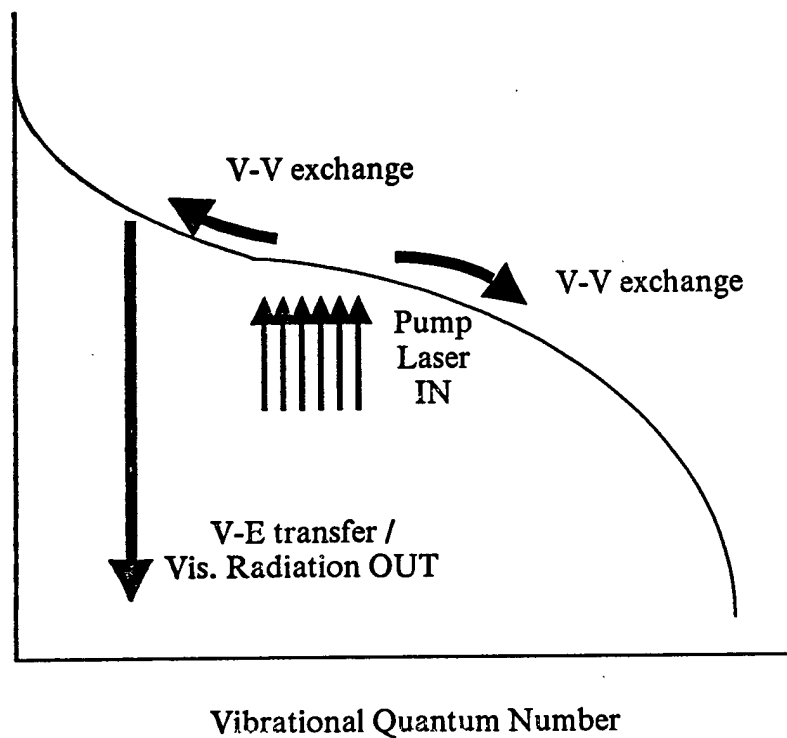
P=1 atm, T=500 K
CO:Ar=1:99

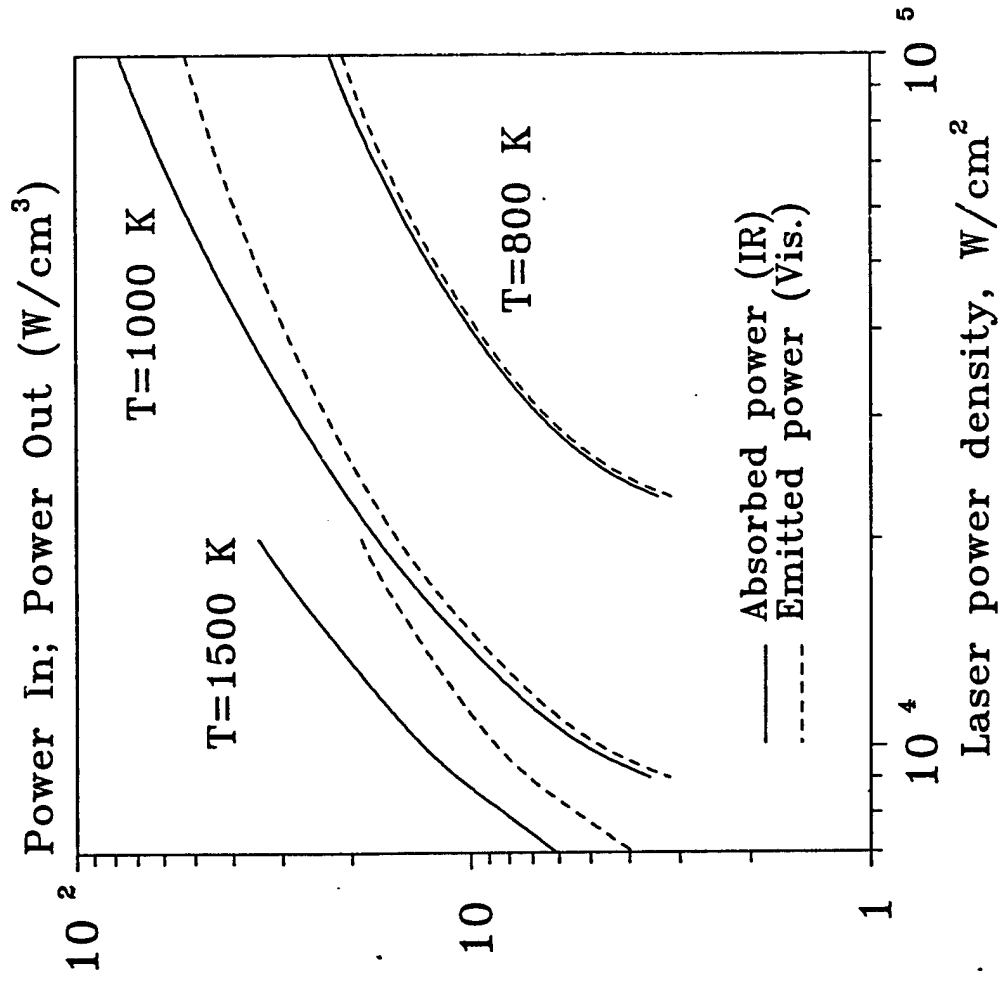


$P=1 \text{ atm}$
 $\text{CO:Ar}=5:95$

**IR/Visible Radiation Conversion
in Optically Pumped CO-N₂-Na Plasma**

Relative population





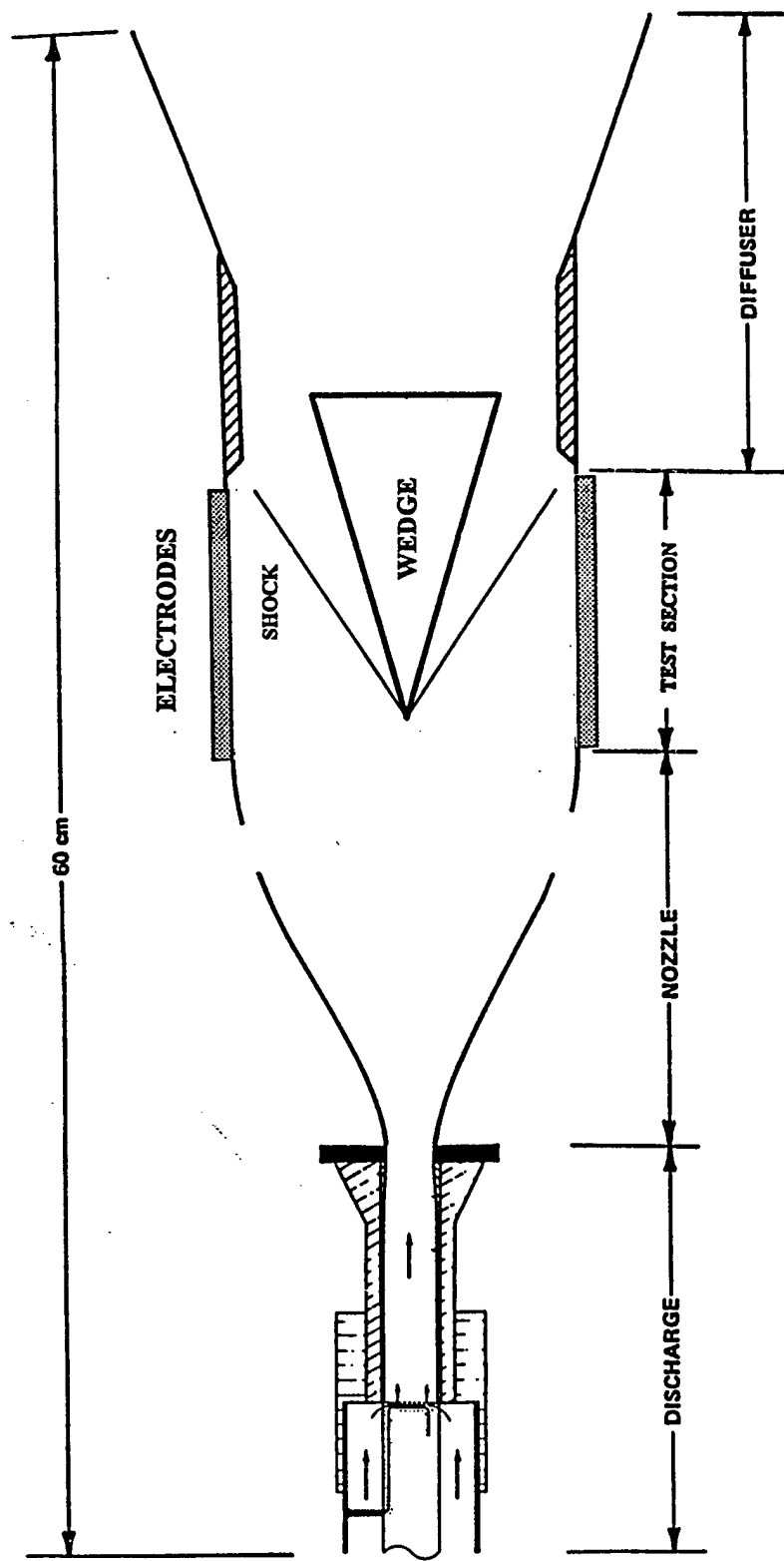
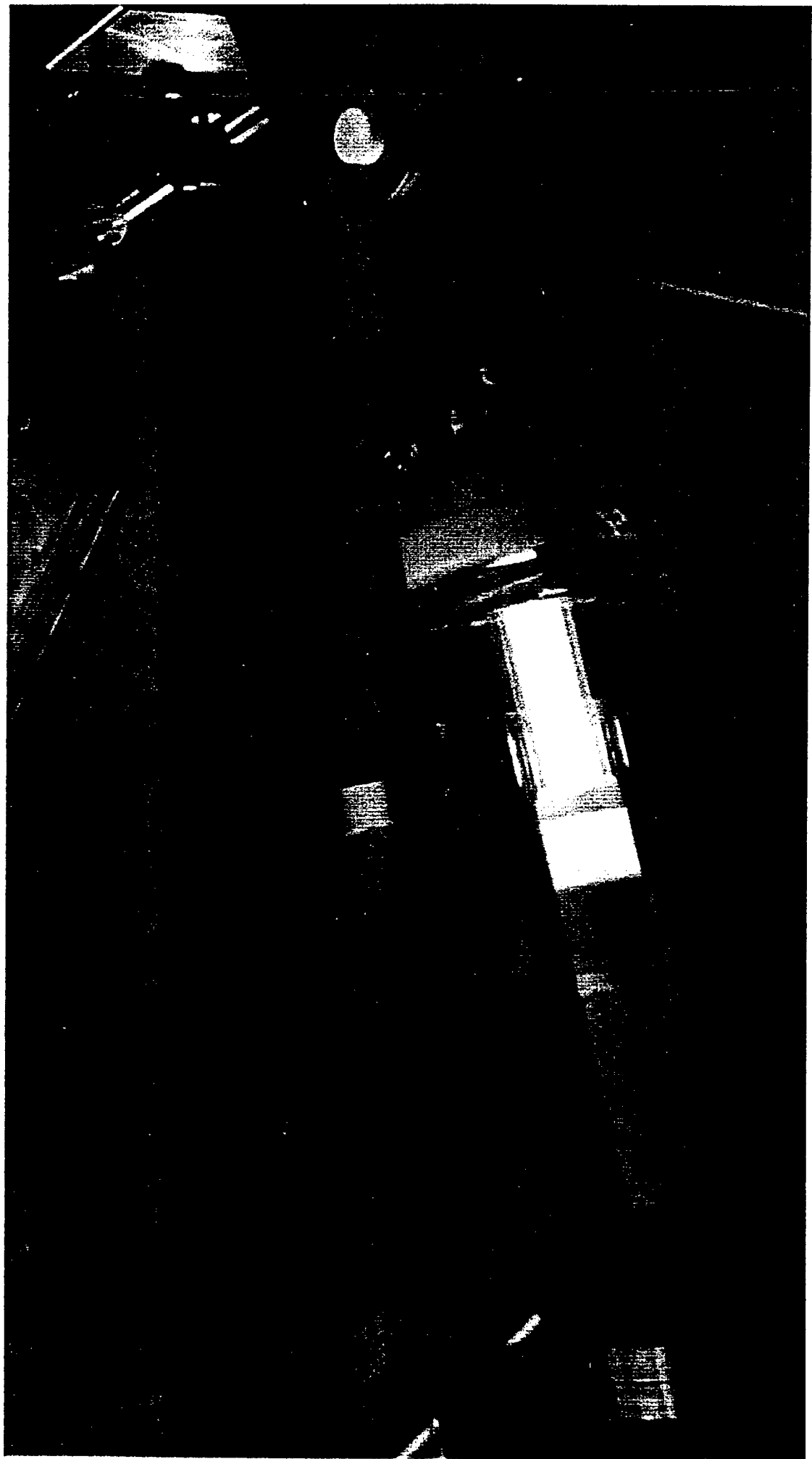


Figure 1. The schematic of the flowing afterglow experiment.



GRADIENT DISTORTION EXPERIMENT

- Transverse temperature gradient is created by absorption of CO laser radiation (1-2% CO is added to the flow to enable absorption and as a thermometric element).

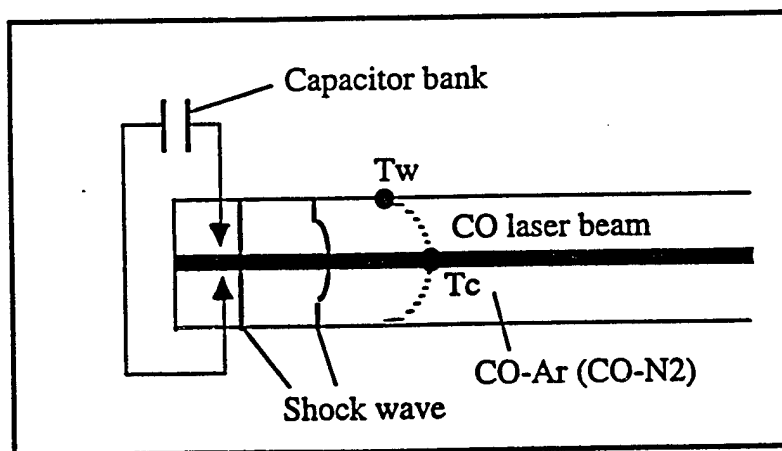
At $P=100$ Torr, $dT/dr \sim 100$ K/cm

Routinely used in CO and NO optical pumping kinetic experiments.

- Plane shock wave created by a capacitor bank discharge.

Measurements of:

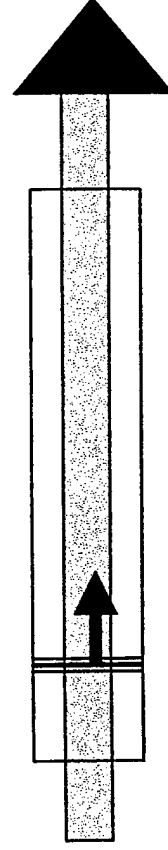
- flow density distribution
- Gas temperature and transverse temperature gradient before the shock arrival



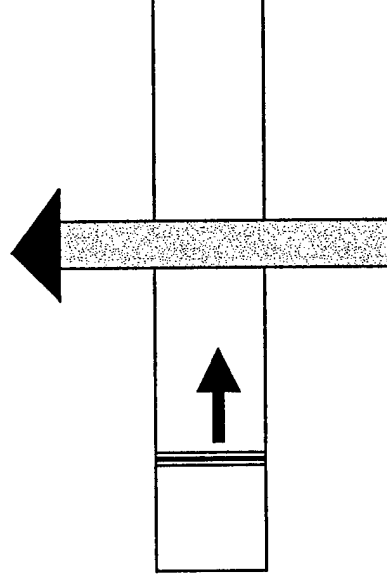
- Radial temperature profile is parabolic:
$$T(r) = T_c - (T_w - T_c)(r/R)^2$$

Experimental verification

- Repeat Ganguly-Bletzinger experiment with thermal effects alone - pure, non-intrusive gas heating induced in CO-seeded Argon, using optical pumping.



Axially directed CO laser beam

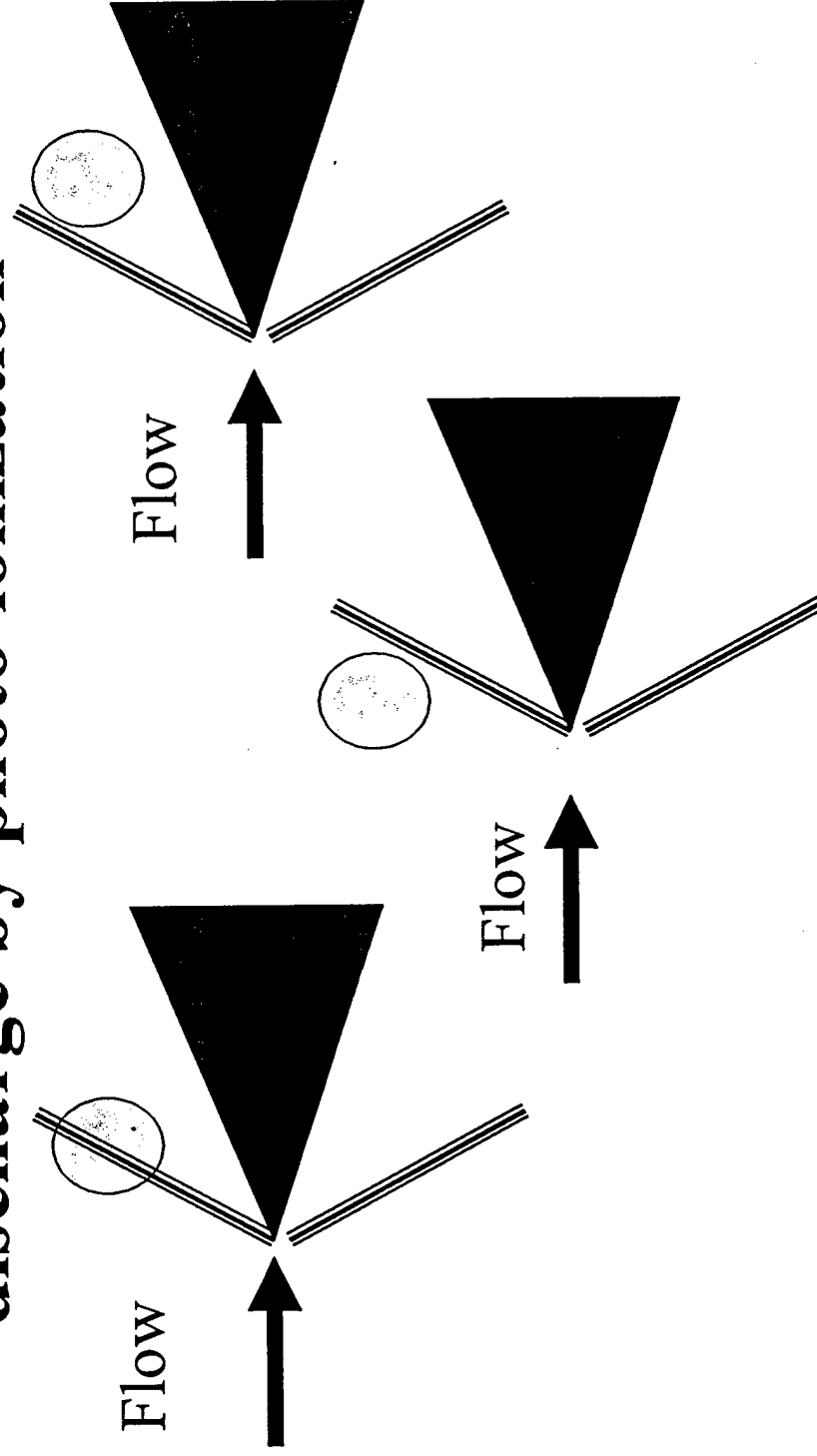


Transverse directed
CO laser beam



Experimental Validation

- Body in wind-tunnel; Thompson discharge by photo-ionization



COMPRESSION
OF A
FIELD-FREE,
NON-HOMOGENEOUS
PLASMA

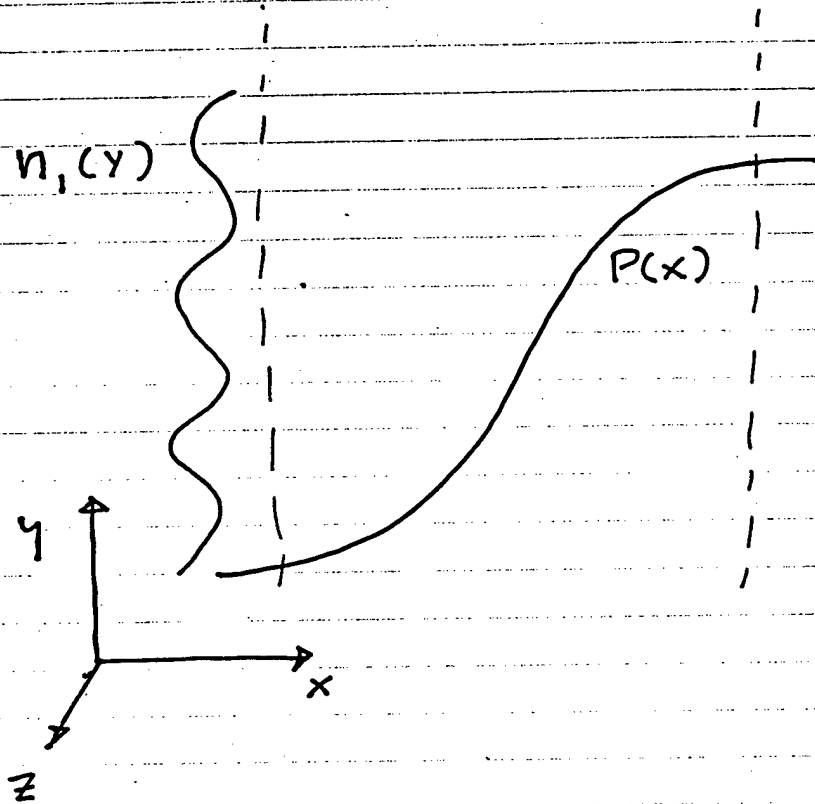
P. J. TURCHI *

AFRL/DE

KIRTLAND AFB, NM

* PROFESSOR OF AEROSPACE ENGINEERING,
THE OHIO STATE UNIVERSITY.

BASIC FORMULATION



OHM'S LAW IN LIMIT
OF HIGH DENSITY
AND LOW CONDUCTIVITY

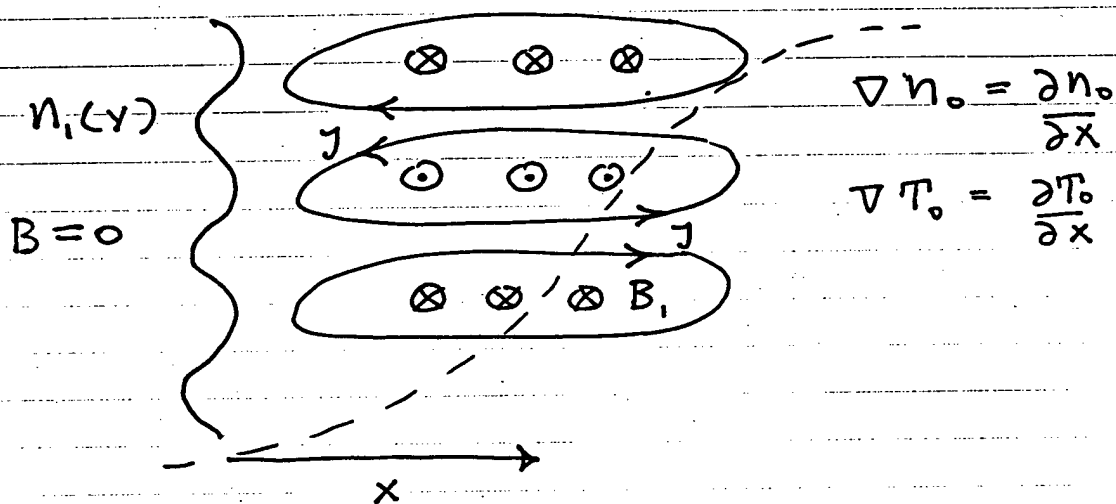
$$\Omega_e \rightarrow 0, R_m \rightarrow 0$$

$$\vec{E} = \eta \vec{j} - \frac{1}{n_e e} \nabla P_e$$

(EXPECTATION THAT PLASMA IS TOO RESISTIVE
INITIALLY TO PERMIT FLUX CONVECTION)

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times (\eta \vec{j}) - \left(\frac{k}{e} \right) \frac{\nabla n_e \times \nabla T_e}{n_e}$$

QUALITATIVE BEHAVIOR



$\nabla n \times \nabla T$ TERM CAUSES GROWTH

OF MAGNETIC FIELD INTO AND OUT OF PLANE

AND ASSOCIATED IN-PLANE CURRENTS

TENDENCY TO TRANSFER AND CONCENTRATE

ENERGY FROM REGIONS OF GENERATION

TO REGIONS OF DISSIPATION

$$P_d = - \vec{E} \cdot \vec{j}$$

(CURRENT DENSITY DIRECTION ALTERNATES
MAIN PRESSURE-GRADIENT INDUCED
ELECTRIC FIELD MAINTAINS DIRECTION)

POSSIBLE NONLINEAR EFFECTS

RESISTIVE HEATING MAY CHANGE PLASMA

$$\eta j^2 \rightarrow \frac{dT_e}{d\eta}$$

CHANGING PLASMA MAY CHANGE TRANSPORT

$$\eta = \eta(n_e, T_e)$$

$$\kappa = \kappa(n_e, T_e)$$

THESE CHANGES GREATLY COMPLICATE THE

ARITHMETIC, BUT MAY BE CRITICAL

FOR DESCRIBING EXPERIMENTAL BEHAVIOR

— FURTHER CONCENTRATION OF
CURRENTS AND IONIZATION

— OPPORTUNITY FOR HEAT TRANSPORT
AT SHOCK VIA HOT COLUMNS

LINEARIZED ANALYSIS

LOOK FOR ELEMENTS OF BEHAVIOR

WITH SIMPLIFIED ARITHMETIC

LET MAIN FLOW CARRY PRESSURE GRADIENT

IN X-DIRECTION $\frac{\partial P_0}{\partial x}$

TRANSVERSE VARIATION OF DENSITY

AND TEMPERATURE AT FIXED PRESSURE

$$\frac{\partial n_i}{\partial y}, \frac{\partial T_i}{\partial y} \quad \text{WITH} \quad \frac{\partial P_i}{\partial y} = 0$$

SOLVE FOR VARIATION OF (WEAK) MAGNETIC

FIELD AS FUNCTION OF BOTH x AND y

$$\vec{B} = B \hat{k} = B_0 + \epsilon B_1(x, y)$$

$$\text{WITH } B_0 = 0 \quad \epsilon \ll 1$$

LINEARIZED ANALYSIS (CONTINUED)

SPECIFY

$$n(x, y) = n_0(x)(1 + \epsilon \sin Ky)$$

AT $\partial P / \partial y = 0$, THEN

$$T(x, y) \cong T_0(x)(1 - \epsilon \sin Ky)$$

$$\text{WHERE } P_0(x) = n_0 k T_0$$

('0' REFERS TO
ZEROth ORDER,
NOT STAGNATION)

ALSO, RESISTIVITY

$$\eta = \eta_0 + \epsilon \eta_1$$

SUBSTITUTION INTO FARADAY'S LAW YIELDS AT $O(\epsilon)$:

$$\begin{aligned} \frac{\partial B_1}{\partial t} = \frac{1}{\mu} \left\{ \eta_0 \left(\frac{\partial^2 B_1}{\partial x^2} + \frac{\partial^2 B_1}{\partial y^2} \right) + \frac{\partial B_1}{\partial x} \left[\left(\frac{\partial \eta_0}{\partial n_e} \right) \frac{\partial n_0}{\partial x} + \left(\frac{\partial \eta_0}{\partial T_e} \right) \frac{\partial T_0}{\partial x} \right] \right. \\ \left. + \frac{K \cos Ky}{e n_0} \frac{\partial P_0}{\partial x} \right\} \end{aligned}$$

STEADY STATE, $\partial B_1 / \partial t = 0$,

$$\begin{aligned} \left(\frac{\eta_0}{\mu} \right) \left[\frac{\partial^2 B_1}{\partial x^2} + \frac{\partial^2 B_1}{\partial y^2} \right] + \frac{1}{\mu} \frac{\partial B_1}{\partial x} \left[\left(\frac{\partial \eta_0}{\partial n_e} \right) \frac{\partial n_0}{\partial x} + \left(\frac{\partial \eta_0}{\partial T_e} \right) \frac{\partial T_0}{\partial x} \right] \\ = - \frac{K \cos Ky}{e n_0} \frac{\partial P_0}{\partial x} \end{aligned}$$

LINEARIZED ANALYSIS (CONTINUED)

TRY SOLUTION OF FORM:

$$B_1(x, y) = b(x) \cos Ky$$

WHICH PROVIDES EQUATION:

$$\begin{aligned} \left(\frac{\gamma_0}{\mu}\right) \left[\frac{d^2 b}{dx^2} - K^2 b \right] + \frac{1}{\mu} \frac{db}{dx} \left[\left(\frac{\partial \gamma_0}{\partial \eta_e}\right) \frac{\partial \eta_0}{\partial x} + \left(\frac{\partial \gamma_0}{\partial \eta_e}\right) \frac{\partial \eta_0}{\partial x} \right] \\ = -\frac{K}{e \eta_0} \frac{dP_0}{dx} \end{aligned}$$

EXPLORE SIMPLER CASE: LET $\gamma_0 = \text{CONSTANT}$

$$\left(\frac{\gamma_0}{\mu}\right) \left[\frac{d^2 b}{dx^2} - K^2 b \right] = -\frac{K}{e \eta_0} \frac{dP_0}{dx}$$

OR

$$\frac{d^2 b}{dx^2} - K^2 b = -\frac{\mu K}{\gamma_0 e \eta_0} \frac{dP_0}{dx}$$

NORMALIZED EQUATIONS

$$\text{LET } P_0(x) = \frac{b_c^2}{2\mu} \beta(\alpha) \quad \text{WHERE } \alpha = x/\lambda$$

$$\text{AND } k = 2\pi/\lambda$$

$$b(x) = b_c f(\alpha)$$

$$n_0(x) = \frac{P_0(x)}{k T_0(x)} = \frac{b_c^2}{2\mu k T_c} \frac{\beta(\alpha)}{\theta(\alpha)}$$

SUBSTITUTION THEN PROVIDES:

$$\frac{d^2 f}{d\alpha^2} - 4\pi^2 f = - \left(\frac{2\pi\mu k T_c}{\gamma_0 e b_c} \right) \frac{\theta(\alpha)}{\beta(\alpha)} \frac{d\beta}{d\alpha}$$

WHICH FURTHER SIMPLIFIES TO:

$$\frac{d^2 f}{d\alpha^2} - 4\pi^2 f = - \frac{\theta(\alpha)}{\beta(\alpha)} \frac{d\beta}{d\alpha}$$

$$\text{BY DEFINING } b_c = \frac{2\pi\mu k T_c}{\gamma_0 e}$$

SOLUTION OF NORMALIZED EQUATION

HOMOGENEOUS PART:

$$\frac{d^2 f_H}{d\alpha^2} = 4\pi^2 f_H$$

$$f_H = c_1 e^{2\pi\alpha} + c_2 e^{-2\pi\alpha}$$

PARTICULAR SOLUTION, WITH FURTHER SIMPLIFICATION $\Theta=1$,

$$\frac{d^2 f_p}{d\alpha^2} - 4\pi^2 f_p = -\frac{1}{\beta} \frac{d\beta}{d\alpha}$$

TRY FORM OF $f_p(\alpha)$ THAT PROVIDES USEFUL FORM

FOR $\beta(\alpha)$:

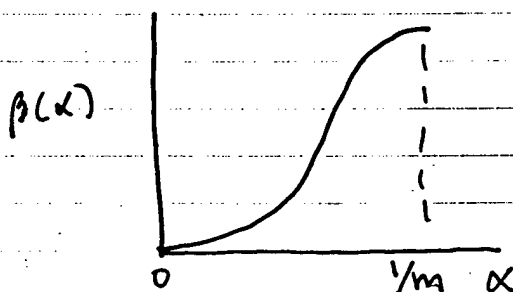
$$f_p(\alpha) = a \sin(m\pi\alpha)$$

THIS GIVES (BY SUBSTITUTION AND INTEGRATION):

$$\beta(\alpha) = \beta_1 e^{\frac{a\pi(m^2-4)}{m} [1 - \cos(m\pi\alpha)]}$$

$$\alpha = 0, \quad \beta = \beta_1$$

$$\alpha = 1/m, \quad \beta = \text{MAXIMUM}$$



THICKNESS OF
PRESSURE RISE:

$$\Sigma = \lambda/m$$

(WHICH GIVES m)

SOLUTION OF NORMALIZED EQUATION (CONTINUED)

WITH $b_1 = 0$ AT $x = 0$ ($f(0) = 0$)

AND $\frac{db_1}{dx} = 0$ ALSO $\frac{df}{dx} = 0$)

THE FULL SOLUTION IS:

$$B_1(x, y) = \frac{\mu k T_0}{\gamma_0 e} \cos\left(\frac{2\pi y}{\lambda}\right) \frac{(\lambda/2) \ln \lambda}{[(\lambda/2)^2 - 4]} \left\{ \sin\left(\frac{\pi x}{2}\right) - \frac{\lambda}{2z} \sinh\left(\frac{2\pi x}{\lambda}\right) \right\}$$

WHERE λ IS THE WAVELENGTH OF
TRANSVERSE PERTURBATIONS OF PLASMA

z IS THE COMPRESSION THICKNESS

AND λ IS THE PRESSURE RATIO

THE SOLUTION IS RESTRICTED TO

$$0 \leq x \leq z \quad \lambda/2 > 2$$

(AND LINEARIZED ANALYSIS)

IT CAN MATCH TO $x \geq z$ WITH UNIFORM PRESSURE,
FOR WHICH B DECREASES EXPONENTIALLY WITH x/λ .

CONCLUDING REMARKS

- INTERACTION OF COMPRESSION WAVE WITH FIELD-FREE, NONHOMOGENEOUS PLASMA CAN GENERATE CURRENT CONCENTRATIONS DUE TO $\nabla n \times \nabla \psi$ PROCESS.
- MAGNITUDES OF CURRENT DENSITIES INCREASE EXPONENTIALLY AS x/λ (FOR LINEARIZED SOLUTION) THROUGH THE THICKNESS OF COMPRESSION
- NONLINEAR EFFECTS IN PLASMA MAY RESULT IN FURTHER CONCENTRATION AND INCREASED TRANSPORT
- THE RESULT OF SUCH CONCENTRATION OF ENERGY AND INCREASED TRANSPORT MAY BE CHANGE IN FLOW STRUCTURE AND RELATED AERODYNAMIC DRAG